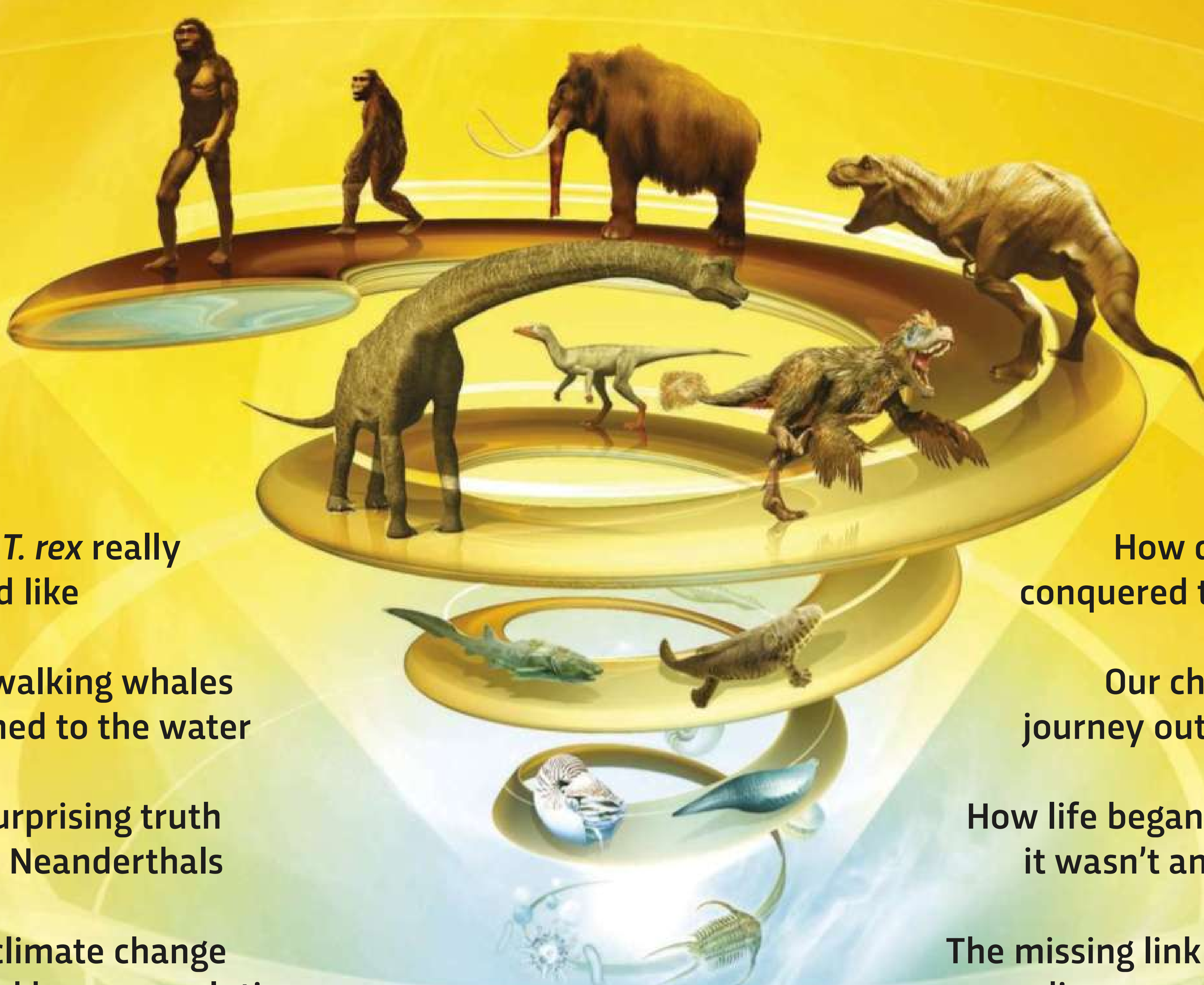
BBC
Science Focus
MAGAZINE
COLLECTION
VOL.13

THE ULTIMATE GUIDE TO ANCIENT LIFE ON EARTH



What *T. rex* really looked like

How walking whales returned to the water

The surprising truth about Neanderthals

How climate change shaped human evolution

How dinosaurs conquered the world

Our challenging journey out of Africa

How life began and why it wasn't an accident

The missing link between dinosaurs and birds

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The social brain

Around 200,000 years ago, our *Homo sapien* ancestors were one of a number of hominin species spread out across the globe. Yet *Homo sapiens* are the only species alive today. How we survived where others didn't is a complex tale with many different storylines and characters. But eventually *Homo sapiens* gained the upper hand – although all non-Africans carry about two per cent Neanderthal DNA, revealing that our ancestors interbred with our stockier cousins.

Why we survived and Neanderthals died out is still controversial. Some academics think that our ancestors outcompeted Neanderthals by being smarter – and that our impressive 'social brains' gave us the advantage. Humans can live in groups of 150 to 200 people, while the maximum for chimpanzees is around 50. If that figure doubles, tensions develop within the troop and it often splits. Neanderthals were the same – fossil evidence suggests that they lived in groups of no more than 20 to 30 individuals. The larger the group, the more brains to solve problems, spread ideas and share technologies.

Just as human evolution didn't follow one simple line of a family tree, but instead was a complex set of branches, it was the same for the evolution of other species throughout ancient history.

This special issue reveals these complex histories through the millennia, starting with the different theories about how life originated on Earth. It reveals how the very first lifeforms evolved from soft bodies to hard shells to backboned beasts walking on four legs. It journeys through the Mesozoic era when dinosaurs ruled the world, explaining how they met their demise and how early mammals prospered in the niches left behind. Finally, it looks at the evolution of mammals and the planetary forces that shaped our own evolutionary journey.

Daniel Bennett, Editor

***Priscacara* is an extinct genus of perch from the middle Eocene.**

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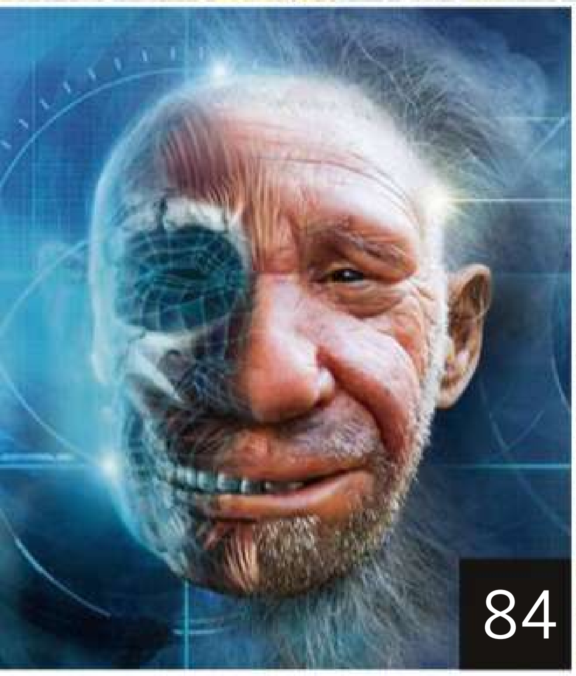

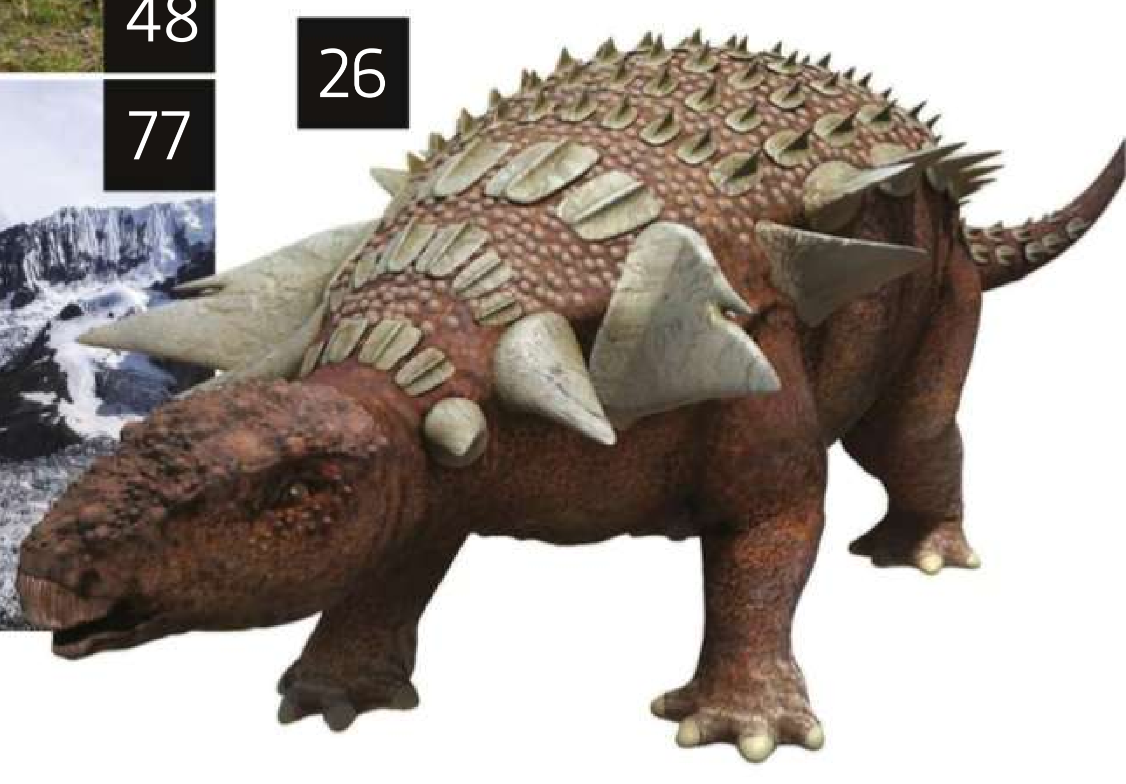

The history of life on Earth

Our Solar System began to develop 4.6 billion years ago from a spinning disk of material. Around 50 million years later, Earth is thought to have collided with another planet (Theia), hurling out debris, some of which stuck together to become the Moon. The gravitational pull of our lunar neighbour helped to stabilise Earth's rotation and get the planet's climate under control.

The first continents and oceans began to form 4,400 million years ago. None of Earth's original crust remains today, but we've found a few crystals of it in Western Australia. The chemistry of these crystals, known as zircons, reveals that by this time Earth had oceans of water – crucial for life.

As Earth cooled around 4,000 million years ago, scientists think that the mantle began to move in predictable patterns, driving the jigsaw of sliding plates known as 'plate tectonics'. This active surface helps to stabilise the planet's temperature and recycles chemical elements, and is believed to be crucial in making it habitable for life.

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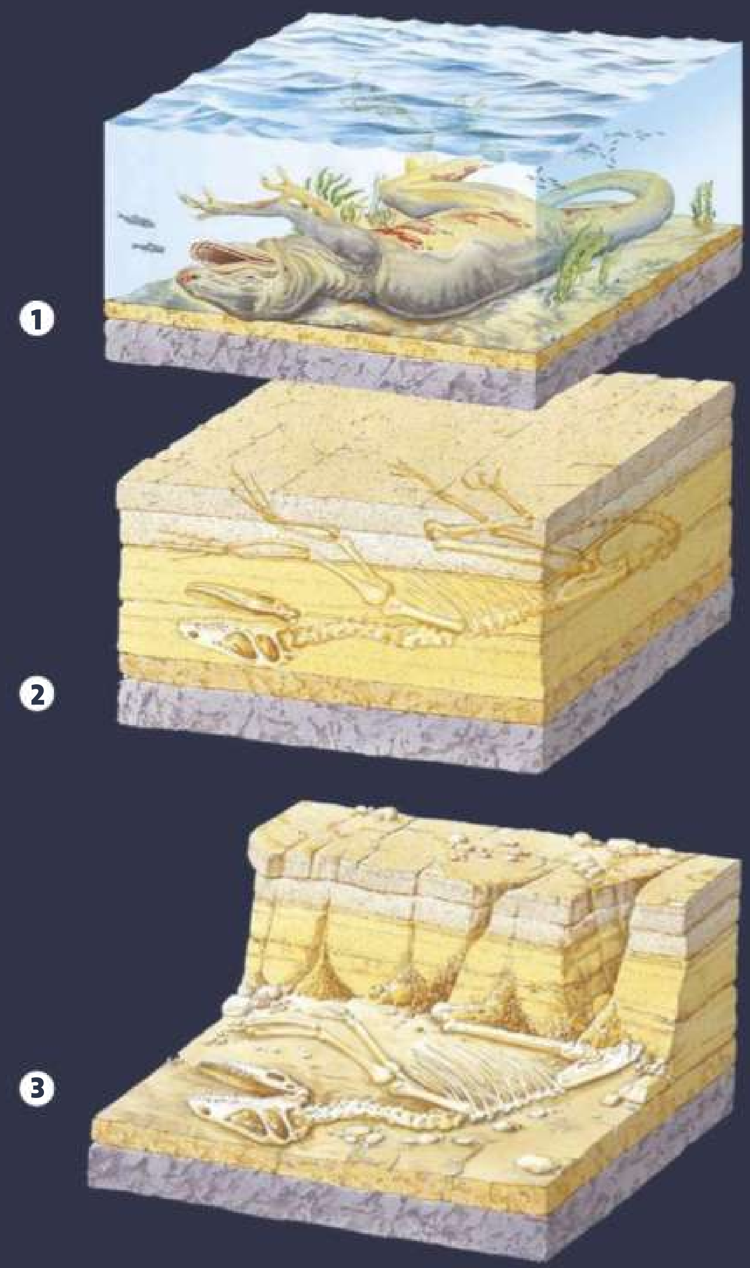


HOW FOSSILS FORM

1. DEATH

Fossils form best in environments without much oxygen that keep out bacteria, such as a stagnant lake or cold sea. These conditions also encourage the chemical reactions that replace the body's soft tissues with hard minerals.

2. QUICK BURIAL

A layer of sediment stops animals from nibbling the flesh and protects the skeleton from being scattered by ocean currents. Shallow seas are good because a constant, gentle rain of dead plankton and sediment is washed down by rivers. And the quicker the burial the better. Sediments turn to rock around the fossil over millions of years.

3. EROSION

The motion of Earth's tectonic plates lifts the fossil above sea level, so erosion can start peeling away the layers of rock above.

THE ORIGIN OF LIFE

There are millions of species alive on Earth today. But how did life get started in the first place?

WORDS: **TOM IRELAND**

THE ORIGIN OF LIFE – HOW LONG AGO WAS THAT?

Around four billion years ago, when the Earth was still partially molten and under heavy bombardment from meteors, the very first life-like systems appeared. Somehow, chemicals developed life-like properties – using matter and energy from the hellish environment to make more of themselves. Origin of life researchers are still trying to work out exactly how, during this period, chemistry suddenly became biology.

Once basic biological systems formed, life never looked back – evolving into the two enormously diverse groups of microbes now known as bacteria and archaea. A merger between two of these ancient cell types, billions of years later, is thought to have given rise to more complex, multicellular organisms – including us, and all the plants, fungi and animals that ever lived.

HOW EXACTLY DID LIFE BEGIN?

Unfortunately, there is no consensus or standard model to explain how life started on Earth. However, most theories are based on the idea that at some point early in the planet's history, chemicals developed characteristics that are found in all living cells today – the ability to self-replicate, for example, or to produce other useful biological molecules.

Once such biological characteristics emerged, a sort of 'chemical evolution' was set in motion: chemicals made copies of themselves, some emerging with variations that made them either more or less efficient, or helped them cooperate with others. The variants that worked best made more copies of themselves, while the others were outcompeted for raw materials.

Over billions of generations, more complex variations emerged, with the basic molecular processes of life enclosed within a membrane. These cell-like structures were essentially

D KELLEY/M ELEND/UNIVERSITY OF WASHINGTON

what is this?

DEEP SEA VENTS

Our most ancient ancestor could be a porous rock. Some scientists believe conditions in deep-sea alkaline vents would have encouraged metabolic-style reactions. Alkaline minerals, reacting with seawater, create concentrated chemicals within tiny pores in the rock. The pores could have acted like the compartments in living cells that generate energy.

the first microbial cells, from which all life evolved.

More fanciful theories suggest that life on Earth was 'seeded' by ancient microbes falling from space.

WHAT IS THE EARLIEST EVIDENCE OF LIFE ON EARTH?

While there are traces of microbes in 3.95-billion-year-old rocks from Canada, the oldest cells ever found are fossilised in rocks dated to around 3 to 3.4 billion years ago. These early cells look a bit like cyanobacteria, which is still abundant today. They were likely to have been thermophiles, meaning they liked hot places, and autotrophs, meaning they made their own complex organic compounds from simple chemicals. Further back in time, there must have been an older type of organism from which these cells evolved.

Other evidence of ancient life can be seen in the form of stromatolites – rocky structures formed from the gritty deposits of vast sheets of ancient microbes floating in the sea. Some of these, found in Western Australia, are thought to be up to 3.5 billion years old, but little is known about the organisms that made them.

The oldest evidence of life on Earth is mysterious traces of a certain isotope of carbon, which researchers think must have been produced by a living organism. Some of this graphite, also found in Western Australia, is thought to have formed around 4.1 billion years ago. This is almost as old as the oldest rocks ever found on Earth, suggesting life may have appeared surprisingly soon after the planet formed.

But what left these tantalising traces? Here the trail goes cold. The theory of how life began, from the innate chemistry of early Earth to those early cells, is a puzzle that remains unsolved.

WHY ARE THERE STILL SO MANY UNANSWERED QUESTIONS?

As well as there being no clear evidence to examine, at the heart of the problem is a paradox. To make the complex biological molecules required for life normally requires other biological molecules. How could any of these intricate molecules be made when biological systems did not exist to make them?

DNA, for example, cannot form by some sort of chemical accident – to make it requires specific enzymes. But to make those enzymes requires the precise instructions carried by DNA.

There are other fundamental problems too – even if complex organic molecules like enzymes and DNA did arise spontaneously, how and why did they begin to cooperate as a system? And how did early life manage to create large organic molecules without the complex energy systems that drive the process in modern cells?

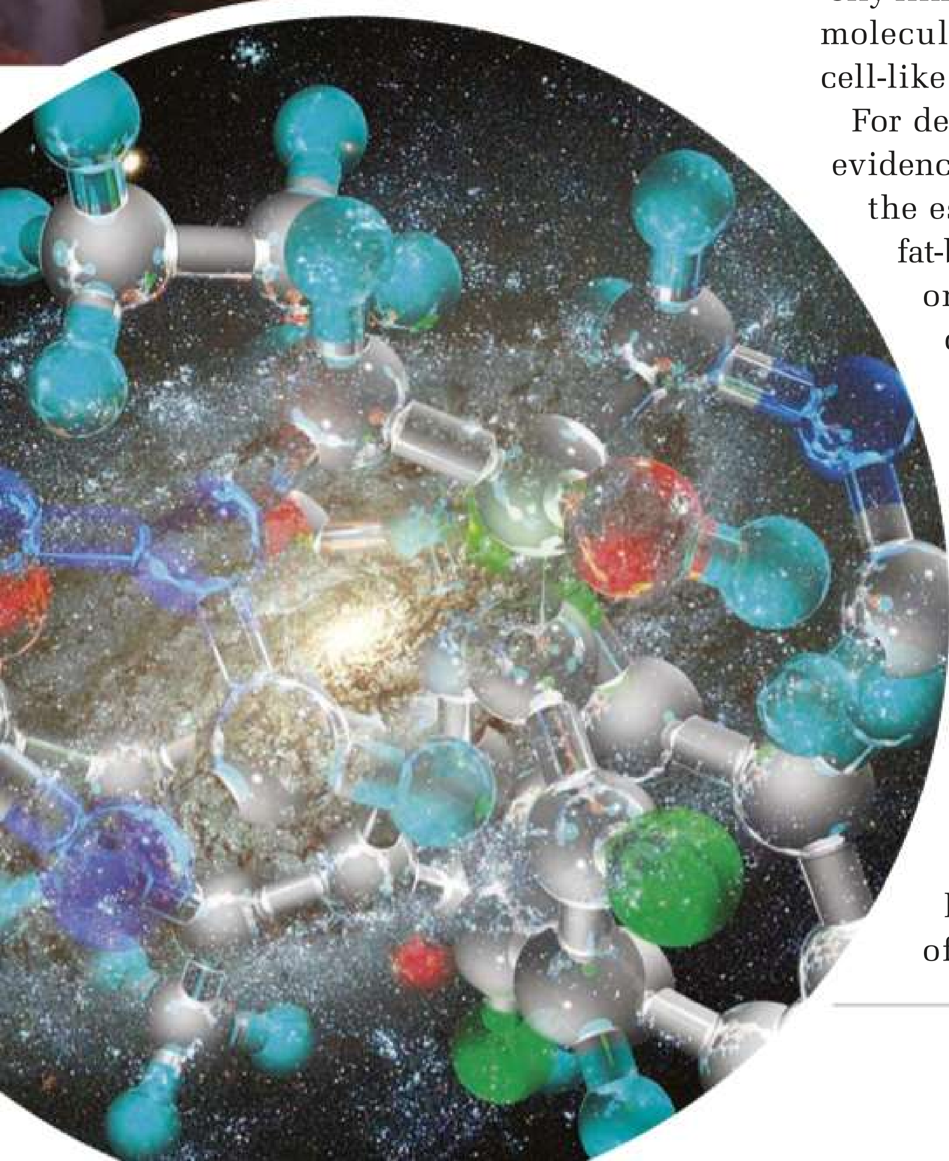
WHAT IS 'PRIMORDIAL SOUP'?

Life is often said to have started spontaneously in a 'primordial soup' – a sort of chemical stock formed in the pools and puddles of early Earth. Charles Darwin once wrote a letter to a friend in which he speculated whether life could have originated in "some warm little

LIFE IS OFTEN SAID TO HAVE STARTED SPONTANEOUSLY IN A 'PRIMORDIAL SOUP' – A SORT OF CHEMICAL STOCK FORMED IN THE POOLS AND PUDDLES OF EARLY EARTH

LEFT: Stromatolites, like these in Australia, formed from ancient microbes up to 3.5 billion years ago

BELOW: Computer visualisation of biomolecules in the Universe



pond somewhere". But it was scientists such as JBS Haldane and Alexander Oparin (who coined the phrase 'primordial soup') and developed the theory in the 1920s. Both said that various chemical compounds could accumulate and become concentrated in locations where hydration and drying regularly occur, such as shorelines, rocky pools or oceanic vents. Cycles of hydration and drying, plus energy from magma, ultraviolet light or lightning, could be conducive to the production of complex organic molecules, they said. Finally, at some point, fat-like molecules could have formed an 'oily film' on the soup that enclosed important molecules within bubbles, forming the first cell-like units.

For decades, however, there was very little evidence to support this idea. It appeared that the essential molecules of life – proteins, fat-based cell membranes, and DNA – were only found in living organisms and could not form without the molecular machinery contained inside cells.

In 1952, a young scientist named Stanley Miller put water, methane, hydrogen and ammonia together in some lab equipment (see 'Life in the lab' on page 12), and frazzled it with thousands of volts to emulate the fierce electrical storms that would have featured in Earth's turbulent atmosphere at the time life first appeared.

Within a few days, the mixture had turned into a rich, brown mix of chemicals, and analysis found

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jargon buster

ABIOGENESIS
The technical term for life originating from non-living matter such as simple organic chemicals. The opposite, biogenesis, means living matter arising from other living matter, which is how life on Earth proliferated once it started.

RNA WORLD
RNA is like a single-stranded version of DNA and performs many important functions in all living cells. Scientists have shown that RNA can spontaneously form a self-replicating molecule, suggesting the Earth was once populated by simple self-replicating RNA forms.

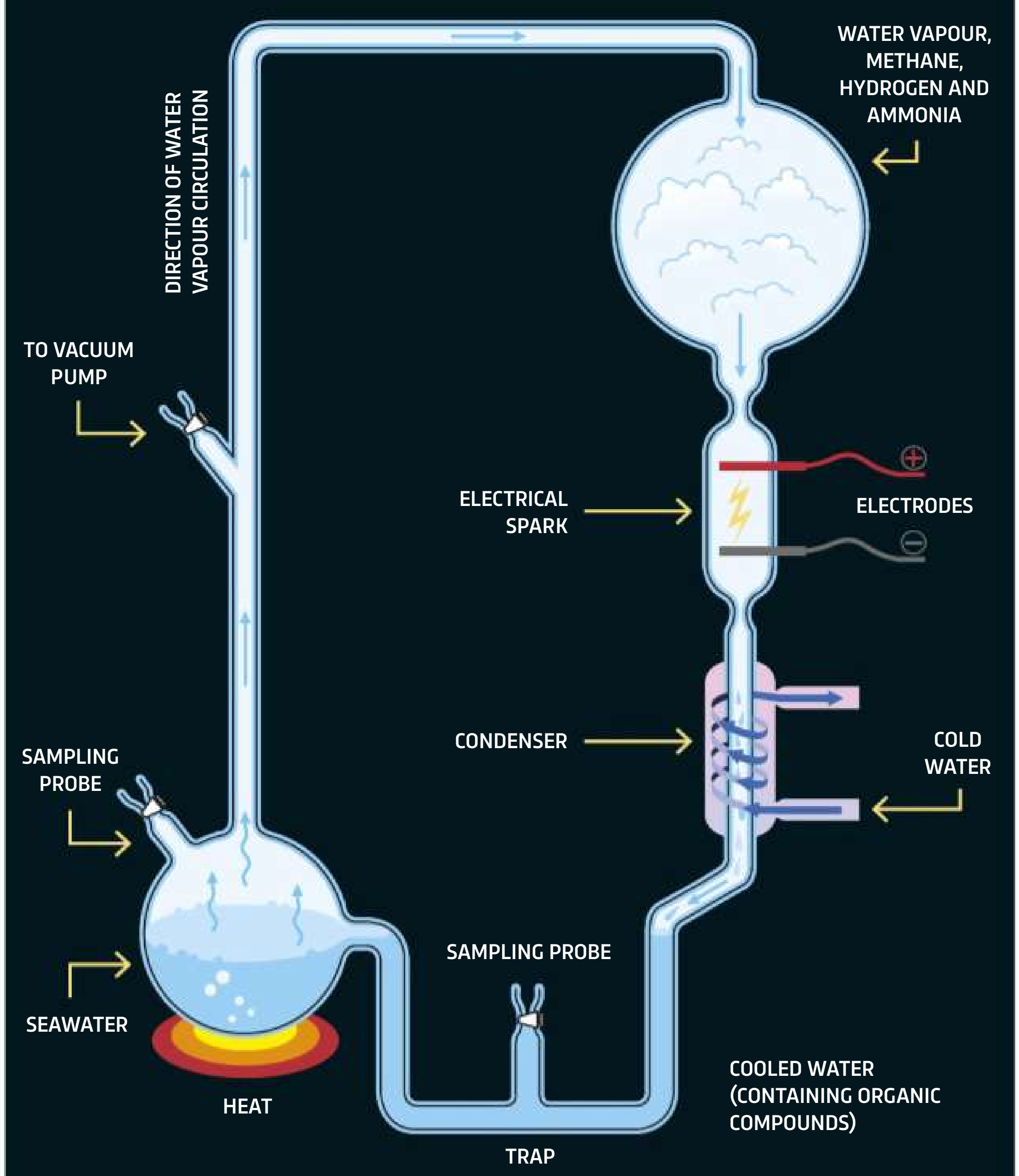
PROTON GRADIENT
Cells can only function properly with energy created by complex metabolic reactions, which generate a difference in chemical charges in different parts of the cell. This is known as a proton gradient. Working out how it could occur spontaneously is a key part of establishing how early life functioned.

LUCA
The Last Universal Common Ancestor is the ancient organism from which all life on Earth is thought to have evolved. Although scientists have a good idea of what LUCA was like, it is a largely theoretical organism. LUCA is likely to have lived around 3.5 billion years ago, just before cells split into two main types: bacteria and archaea.

PANSPERMIA
The idea that life evolved after travelling to Earth from space.

LIFE IN THE LAB

Scientist Stanley Miller combined seawater and various gases together to replicate the ocean and the atmosphere. He introduced electricity to simulate a lightning storm. The process generated amino acids – the building blocks for life.



EVEN WITH A 'SOUP' STOCKED WITH THE INGREDIENTS OF LIFE, IT'S ENORMOUSLY DIFFICULT TO GET THESE INGREDIENTS TO FORM VERY COMPLEX BIOCHEMICALS

that amino acids – the building blocks of proteins – had formed spontaneously.

The experiment was key in supporting the view that life could arise from simple chemicals on the surface of the Earth. Modern analysis has since found that all 22 of the essential amino acids required for life can be made like this. Scientists have also since made other important biological chemicals in similar ways, such as nucleotides, the building blocks of DNA.

So did life form in the primordial soup? Well, this approach only gets us so far. Even with a 'soup' stocked with the ingredients of life, such as amino acids and nucleotides, it's still enormously difficult to get these ingredients to form very complex biochemicals such as proteins or DNA. And it's even more difficult to make versions of those molecules with meaningful biological functions.

WHERE ELSE COULD LIFE HAVE FORMED?

Another theory gaining credibility is the idea that life began in hydrothermal vents in the deep oceans. At the time of life's origin, the seawater was acidic and positively charged. In contrast, the vents ejected negatively charged, alkaline substances.

These fissures in the Earth's crust, where alkaline minerals reacted with acidic seawater, created tiny pores in rocks, which appear to concentrate chemicals produced by other reactions in the vent.

Iron- and sulphur-based minerals in the vents could have helped catalyse reactions, just like iron- and sulphur-based proteins do in modern cells. Today, such vents often host complex microbial communities, fuelled by the chemicals dissolved in the vent fluids.

The most exciting aspect of this theory, however, is the complex chemistry occurring between the inside and the outside of the microscopic pores. This could create what is known as a 'proton gradient' – an absolutely key part of the way all organisms store energy and use it to build complex molecules.

The final stage in the theory again involves the production of fatty molecules, which can spontaneously form bubble-like, cell-like spheres. Having been produced in the chemical froth, some of these bubbles could have enclosed

self-replicating sets of molecules – forming the very first organic protocells.

COULD LIFE HAVE COME FROM SPACE?

The idea that life originated in space, known as panspermia, is not as wacky as it sounds. Scientists have found lots of unexpectedly complex molecules, such as amino acids or small components of DNA, nestled on comets or meteorites that have crashed to Earth.

Most scientists say that these chemicals, at best, simply 'stocked the soup'. There is no evidence that cells or more complex biological molecules, such as protein or DNA, have travelled to Earth from space.

SO WHAT WAS THE FIRST BIOLOGICAL MOLECULE?

The holy grail of origin-of-life research is understanding which chemicals developed life-like properties first and how they began to work together.

The fact that DNA carries the instructions for life suggests it was central to early life. But researchers are increasingly focused on another molecule, RNA, as potentially the first chemical to come to life.

RNA is similar in structure to DNA and performs lots of key functions in cells, from making proteins to translating and communicating the genetic code. 'RNA world' is the name given to the theory that before DNA, self-replicating RNA units began to proliferate, and evolved complexity.

Researchers making random sequences of RNA have found that some can form complex shapes, which help them perform various functions, such as acting as a catalyst for the production of other molecules.

Scientists have managed to create an RNA molecule that helps to create more of itself. This 'protogene', known as R3C, lends exciting support to the idea that chemicals can develop life-like properties such as self-replication.

Other theories suggest that life began with a much simpler version of DNA and RNA – one that was easier to form from the chemicals of early Earth. This then evolved into the amazingly robust and efficient information-carrying molecules that we see today.

Prof Nicholas Hud, from the NASA-funded Centre for Chemical Evolution in Atlanta, believes there may have been several biological molecules coexisting at one point, and 'life' as we know it started when they began to cooperate.

"I don't subscribe to the view that there was one first self-replicating molecule," says Hud. "I believe we are descendants of the polymers that started to work together. Four types of polymer essentially form most of the metabolism of life: lipid membranes, [sugars], proteins and nucleic acids. These are the survivors of perhaps many different polymers."

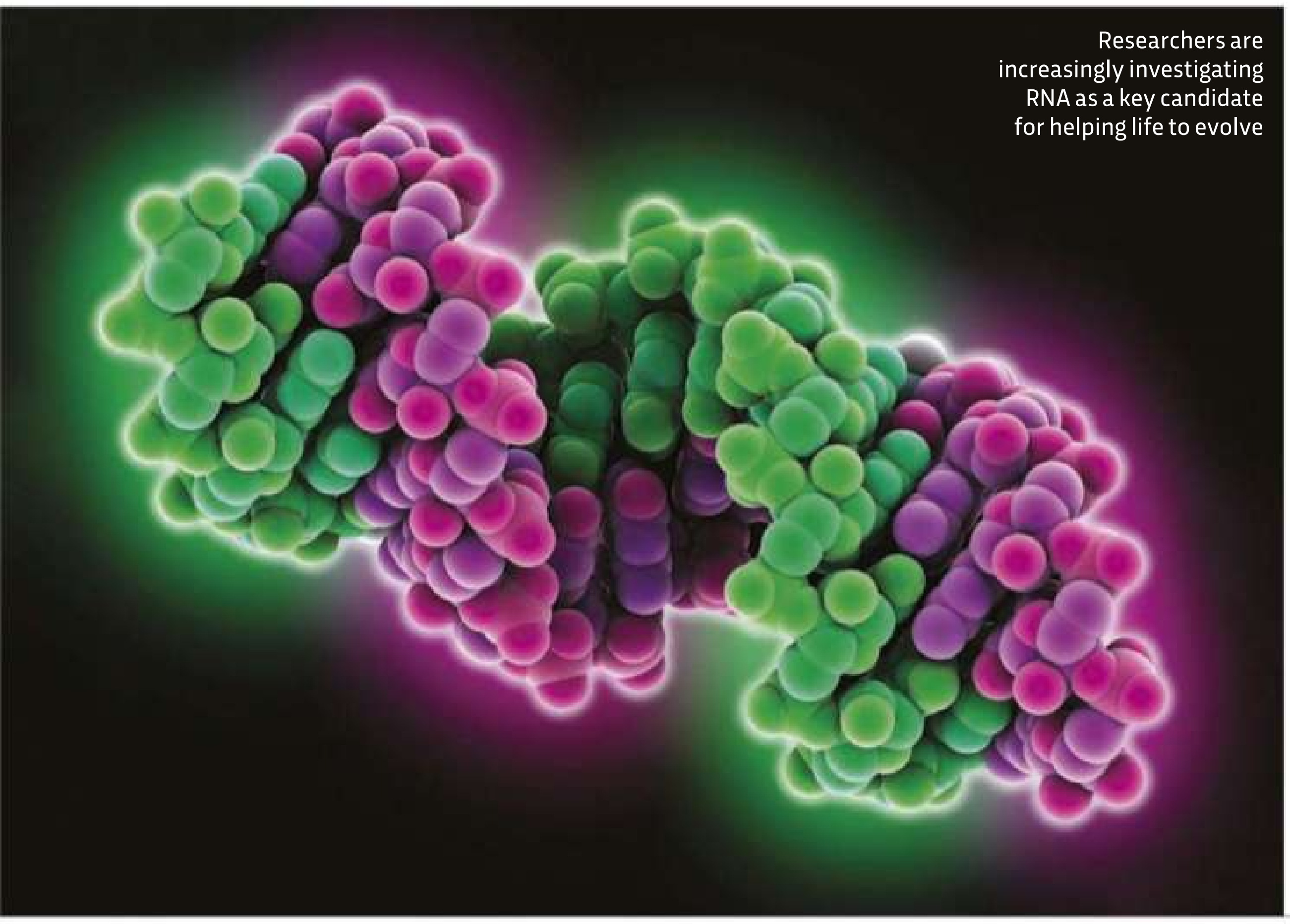
ARE THERE OTHER THEORIES?

There are dozens more theories, some of which are subtly different versions of the ones above, some of which are more left field. Many are based around conditions that might have helped concentrate important biochemicals and protect them from degradation, such as the 'clay theory' – which suggests crystals in clay could have helped arrange organic molecules into organised patterns.

Others attempt to deduce the order in which the molecules of life formed and began to cooperate. One example is the 'lipid world' theory, which suggests that membrane-like bubbles of fatty molecules were the first

BBC RADIO 4

*Listen to an episode of **The Infinite Monkey Cage** on the origins of life:* bbc.in/KEsSpt



Researchers are increasingly investigating RNA as a key candidate for helping life to evolve

step towards cellular life. Although these wouldn't be information carrying units, like RNA or DNA, they may have been able to produce more of themselves and RNA might then have formed more easily within them.

WILL WE EVER FIND A SATISFACTORY ANSWER?
Scientists working on this problem still disagree on the fundamentals. Speaking to origin-of-life researchers at times sounds like they are moving further away from a consensus, rather than closer. Dr Nick Lane, a biochemist and author of the origin-of-life book *The Vital Question*, says the problem is even harder to solve than those posed by theoretical physics: "We are not even in the position of the physicists, where everyone at least agreed what the question was and could build a huge machine, like the LHC, to look for the answer. We are still miles away from that agreement."

But despite the lack of a unifying theory, many scientists are confident of finding a solution. Increasingly, they're using computer modelling to investigate how certain mixtures of molecules might behave over time. "I don't think I'm that far away…" says Lane, semi-seriously.

"The key message is that the nuts and bolts of all life is almost identical," says Matthew Powner, a chemist studying the origin of life at University College London. "The difference between us and a tree seems obvious, but people often don't understand how similar the biochemistry that it's all built from is, using very few chemical species. Eight nucleotides, 20 amino acids and a few lipids, and you don't need much else."

The overall solution may not have been solved, but each life-like molecule that emerges from a lab is another piece of the puzzle found. As broadcaster and geneticist Adam Rutherford concludes in his book *Creation: The Origin Of Life*, "That first time had millions of years, whereas scientists have made these replicators in a decade. It is important to remember that we know the answer: Life is the answer. The question is finding a believable route to get there." SF

by TOM IRELAND *(@Tom_J_Ireland)*
Tom is the editor of ***The Biologist*** *magazine.*

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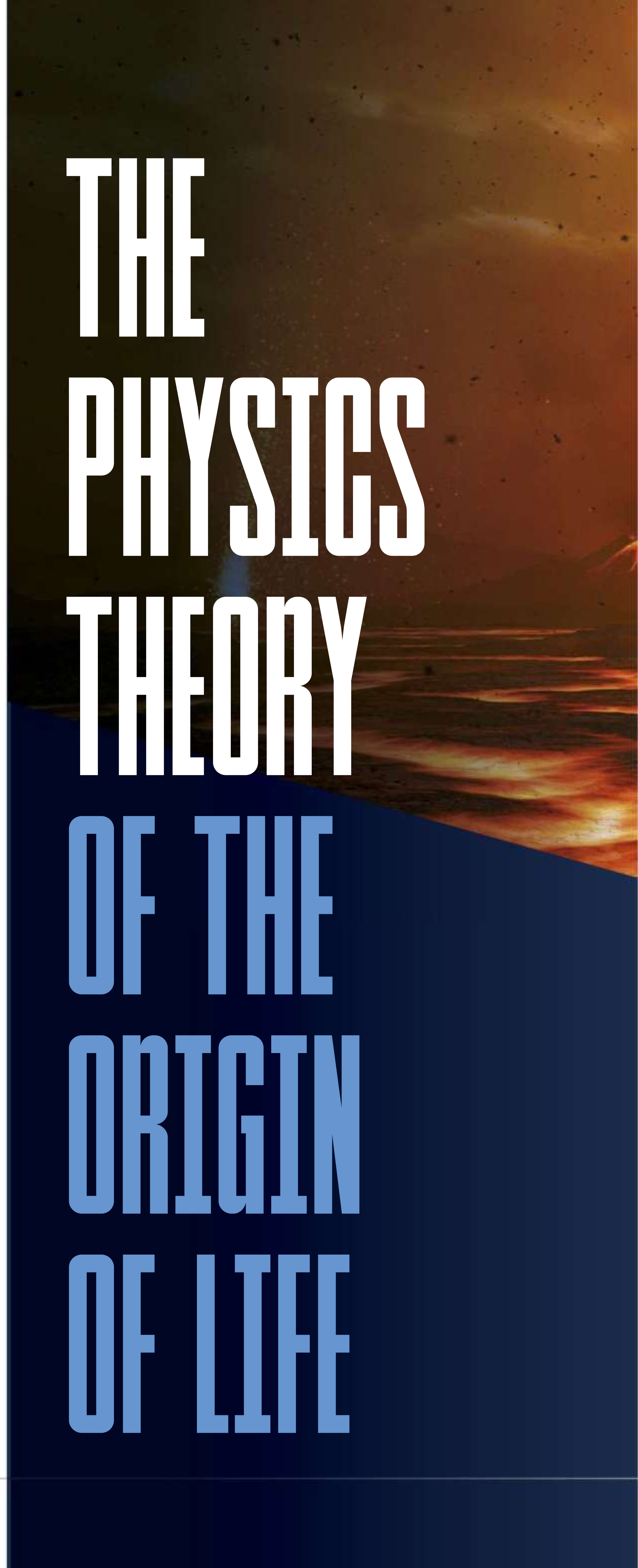


THE PHYSICS THEORY OF THE ORIGIN OF LIFE

Could physics explain how life emerged on early Earth?

Move over, biology. Physics is enjoying a starring role in a new theory about how life first emerged from the primordial goo

WORDS: **BRIAN CLEGG**

From the expansion of the Universe to the motions of the tiniest subatomic particles, modern-day physics can help us interpret a dizzying number of natural phenomena. But can it explain how life as we know it begin? Dr Jeremy England, assistant professor of physics at the Massachusetts Institute of Technology (MIT), thinks it can. He is currently working on a bold theory that hopes to reveal how life-like behaviours could emerge from an inert collection of chemicals.

"I was always interested in how the physics of big, messy assemblies of particles becomes life-like, ever since I was doing research on protein folding as an undergraduate," says England. "It was the way I could successfully refuse to choose between theoretical physics and biology – both were fascinating to me."

England's work is based on the well-established physics of thermodynamics – the science that describes how heat moves from place to place and is crucial for many natural processes. He calls his theory 'dissipative adaptation', as it aims to describe how structures emerge and change through the dissipation of energy, primarily heat, into their environment. This process increases the entropy (the amount of disorder) in the surroundings, which Austrian quantum physicist Erwin Schrödinger identified as necessary for living organisms to function. Crucially, the increase in entropy makes it possible for the evolving structures to stay in what is known as a 'non-equilibrium state'.

Usually a system (which could mean anything from a box of gas to a complex structure) comes into equilibrium with its environment. This means that there is no net flow of heat between the system and its

surroundings. For example, if you leave a cup of hot tea on the table, it will eventually reach the same temperature as the room, much to the chagrin of the tea-lover who was looking forward to a cuppa. But living things are in a non-equilibrium state, taking energy from sources such as sunlight and food, and pushing that energy out – 'dissipating' it – into their surroundings. This enables a living organism to reduce its own entropy, so it can grow and build structure. And it is the physics of such non-equilibrium states that England and his team investigate, by using computer simulations to look for situations where life-like behaviours emerge spontaneously.

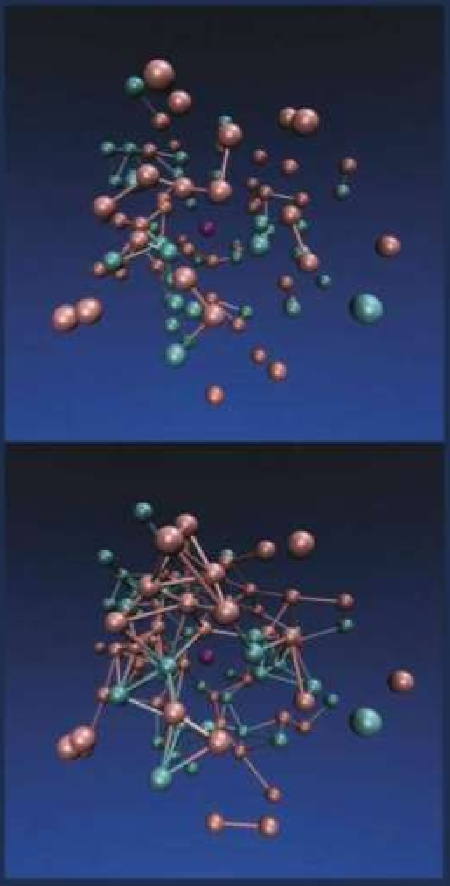
BEYOND BIOLOGY

This is not the first time that a physicist has attempted to take on the deeper questions of biology. In 1944, Schrödinger published a book based on a series of lectures he had given in his adopted home of Dublin. The book, *What Is Life?*, emphasised the central significance of energy flows and entropy. In the book, he also suggested that biological inheritance would depend on what he called an 'aperiodic crystal' – a molecule that could carry information in its structure – a prediction that was fulfilled with the discovery of the structure of DNA.

"The beginning point of my current line of research – which really has veered away from biology, at this point – was realising that to think about the physics, you have to take what's interesting about life and break it into separate well-defined physical phenomena that you can then talk about in terms of thermodynamics. So, for example, living things make copies of themselves but not all self-replicators are alive," says England.

The behaviours that England is targeting include reproduction, harvesting energy, natural selection and the ability to anticipate the future. Sometimes these effects can be seen in simple, familiar phenomena that bear no resemblance whatsoever to life, such as snowflakes and sand dunes, he says. But in both cases, these structures are able to form as a result of releasing energy into the surroundings. "In the case of a snowflake, it's the heat released by the exothermic [heat-emitting] crystallisation of liquid water into solid ice," he says. "In the case of a sand dune, the flowing air gets the sand grains moving, but then they stop again because they rattle against each other and lose that energy as heat to the surrounding air."

The evolutionary history of an organism is stored in its DNA, moulding its current form. England believes that an organism's history of



ABOVE: This computer simulation by Jeremy England shows particles in a gooey fluid. The turquoise particles are being driven by an oscillating force, which leads to bonds forming over time

ABOVE RIGHT: Snowflakes are complicated, forming due to liquid water crystallising into ice, but they are not alive

WHAT IS ENTROPY?

Thermodynamics' second law sounds trivial when described in simple terms as 'heat moves from a hotter body to a colder body', but there is much more going on. It's involved in everything from life to the ultimate fate of the Universe.

An alternative, more technical description of the second law is that 'in a closed system, entropy stays the same or increases'. Entropy is a mathematical measure of the amount of disorder in something, based on the number of different ways that you can rearrange the object's parts. Broadly speaking, the more disordered a system is, the higher its entropy.

Take this magazine. There's one way to arrange the letters to make the magazine readable. There are also vast numbers of other ways the same letters could be arranged, but they wouldn't make sense.

The second law also tells us that over time entropy will increase – everything runs down and decays. Such an increase in entropy explains why it's much easier to break a glass than unbreak it.

With this in mind, it may seem highly unlikely that living organisms could have ever developed. This is where the 'closed system' bit of the law comes in. If you put energy into a system from the outside, it's possible to reduce entropy within it – the entropy of the energy source and the 'closed system' will still increase.

"LIFE IS GOOD AT ENERGY HARVESTING AND SELF-REPAIR. WE MAY BE ABLE TO GET IT TO SELF-ORGANISE AS WELL"

dissipating heat and therefore increasing entropy also help shape its structure. Without DNA to act as a record of changes, England believes that the physical form of the structures can hold information.

"Think about a glass being sung at by an opera singer, and it resonates and violently changes its shape and shatters. Once it shatters, it is much worse at absorbing energy from the song, as it is a pile of shards. It changes its shape much less, it has become much more stable," he says. "But those shards are not a random arrangement of glass, they contain a lot of information about the shape the glass was in when it shattered. So even though they are bad at absorbing energy, they have a signature of a moment in history when the opposite was the case, which can be reconstructed with the right detective work."

Sometimes, in the team's simulations, a surprising level of self-organisation emerges. For example, when they begin with a virtual soup of different simulated chemicals interacting, some start to take over at the expense of others. They then begin to dominate as they prove better at harvesting the available energy.

"There are lots of things we think of life being distinctively good at, for example energy harvesting, predictive computation [anticipating the future] and self-repair, that we may be able to get to self-organise even in the absence of Darwinian evolution by self-replication and natural selection," says England.

A STARTING TOOLBOX

Though still in the early stages, the theory is not without its critics, and England himself agrees that there is a huge gap between simply observing life-like behaviour and life itself.

"All life we see is the product of countless competing of past generations of things that were already alive and got to co-evolve for a long time," he says. "Also, any living thing is a composite of many distinctively life-like behaviours, and they do not necessarily all come hand-in-hand at the outset. For example, something could be a very good energy harvester and not necessarily be in any way capable of self-replication, and I do not claim to know anything about how the package deal we call life first gets bundled together."

What he does believe, however, is that his team's work is enriching what he calls the "starting toolbox" for life to form. For the moment, their work is purely based on computer simulations, though other researchers are starting to take up the idea and work on investigating similar thermodynamic effects in physical experiments.

We may not have the answer to how life began yet, but dissipative adaptation gives us a clearer picture of one of the fundamental principles that has encouraged the emergence of living things. SF

by BRIAN CLEGG *(@brianclegg)*
Brian is a science writer. His latest book is The Graphene Revolution.

GETTY IMAGES X2, JEREMY ENGLAND

what is this?

CRINOID FOSSILS

Scyphocrinus elegans are an extinct species of crinoid dating from the Silurian/Devonian period, around 443-358 million years ago. Crinoids are marine echinoderms. These particular ones had stalks which they would have used to attach themselves to the seabed, capturing food with feathery arms that formed a cup. Thousands of extinct crinoid species have been found as fossils, but only a few hundred species still exist today.

THE DAWN OF LIFE

How the first lifeforms evolved on Earth from soft-bodied organisms to hard-shelled creatures to four-legged animals…

WORDS: **JOHN PICKRELL**

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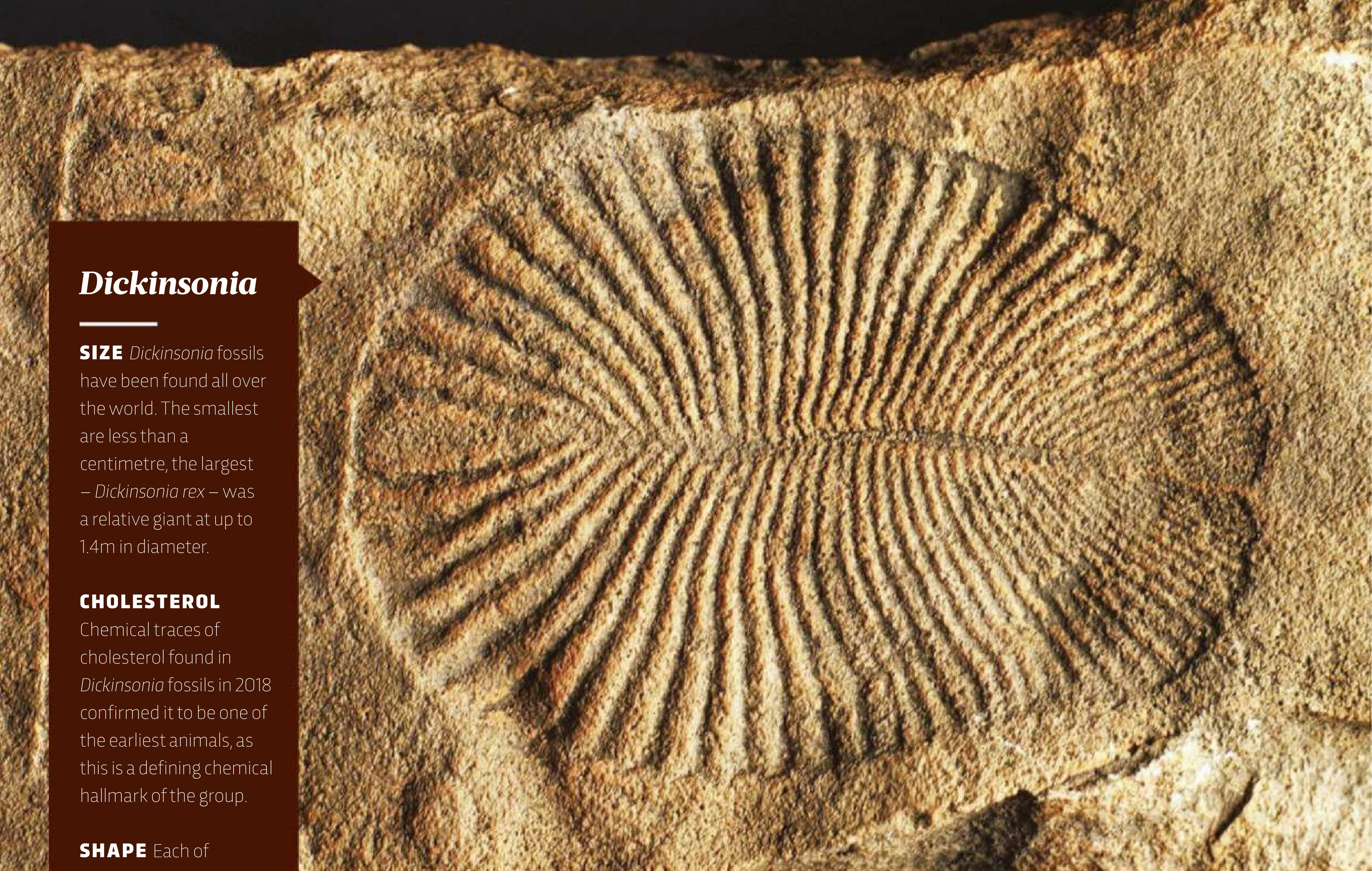
Fossilisation is so rare that fewer than one per cent of all the species that ever lived have ended up as fossils. Nevertheless, we have found so many in recent years that palaeontologists have pieced together many of the major evolutionary steps that were taken to arrive at the startling profusion of life we see today. Beginning with mere traces of microbes in 3.95-billion-year-old rocks from Canada, the ever-increasing complexity and diversity of life can be traced through the evolution of multicellularity and the first large animals, and then the sudden appearance of many invertebrate groups in the Cambrian Explosion 541 million years ago. Subsequent developments in vertebrates included backbones, jaws and limbs. The invasion of Earth's landmasses by plants 470 million years ago and four-limbed tetrapods 395 million years ago, meant the journey to the modern world was well underway…



Dickinsonia

SIZE *Dickinsonia* fossils have been found all over the world. The smallest are less than a centimetre, the largest – *Dickinsonia rex* – was a relative giant at up to 1.4m in diameter.

CHOLESTEROL Chemical traces of cholesterol found in *Dickinsonia* fossils in 2018 confirmed it to be one of the earliest animals, as this is a defining chemical hallmark of the group.

SHAPE Each of *Dickinsonia*'s segments may have been inflated with fluid, giving it the appearance of a plump, quilted mattress.

MOVEMENT It was one of the few Ediacarans that was mobile and a sequential series of up to 13 'footprints' of its body have been found on the seafloor.

HEAD END *Dickinsonia* may have had a front (and a rear), but many Ediacaran creatures had no discernible head or mouth, and most likely absorbed nutrients through their bodies.

EDIACARAN PERIOD | 635-541 million years ago

EDIACARAN BIOTA

FOR THE FIRST several billion years of life on Earth, bacteria ruled. But the discovery in Australia in 1946 of fossils of weird, soft-bodied creatures showed that by 550 million years ago ecosystems of larger, multicellular organisms had evolved. Named after the Ediacara Hills of the South Australian outback where they were first discovered, these creatures presented a puzzle for researchers who debated whether they were lichens, animals or an entirely different branch of the tree of life that left no descendants.

Most Ediacarans are simple-looking creatures that may have filtered nutrients from the water column or absorbed them through their bodies from a bacterial slime layer that carpeted the seafloor. Some are likely to be ancestors of living groups such as corals, jellyfish and molluscs, but as nothing was yet hunting and eating anything else, they were yet to evolve defences like shells.

Spriggina (left) was unlike other Ediacarans in that it may have had a head and segmented plates. It may be that this 3-5cm-long, soft-bodied species was an early arthropod, the group to which insects, crabs, spiders and trilobites belong.

Did you know?

NASA has been funding research into Ediacaran fossils in Australia, as it believes these strange creatures might be a good starting point for detecting and recognising any potential simple extra-terrestrial life that may exist on moons around other planets in our Solar System.

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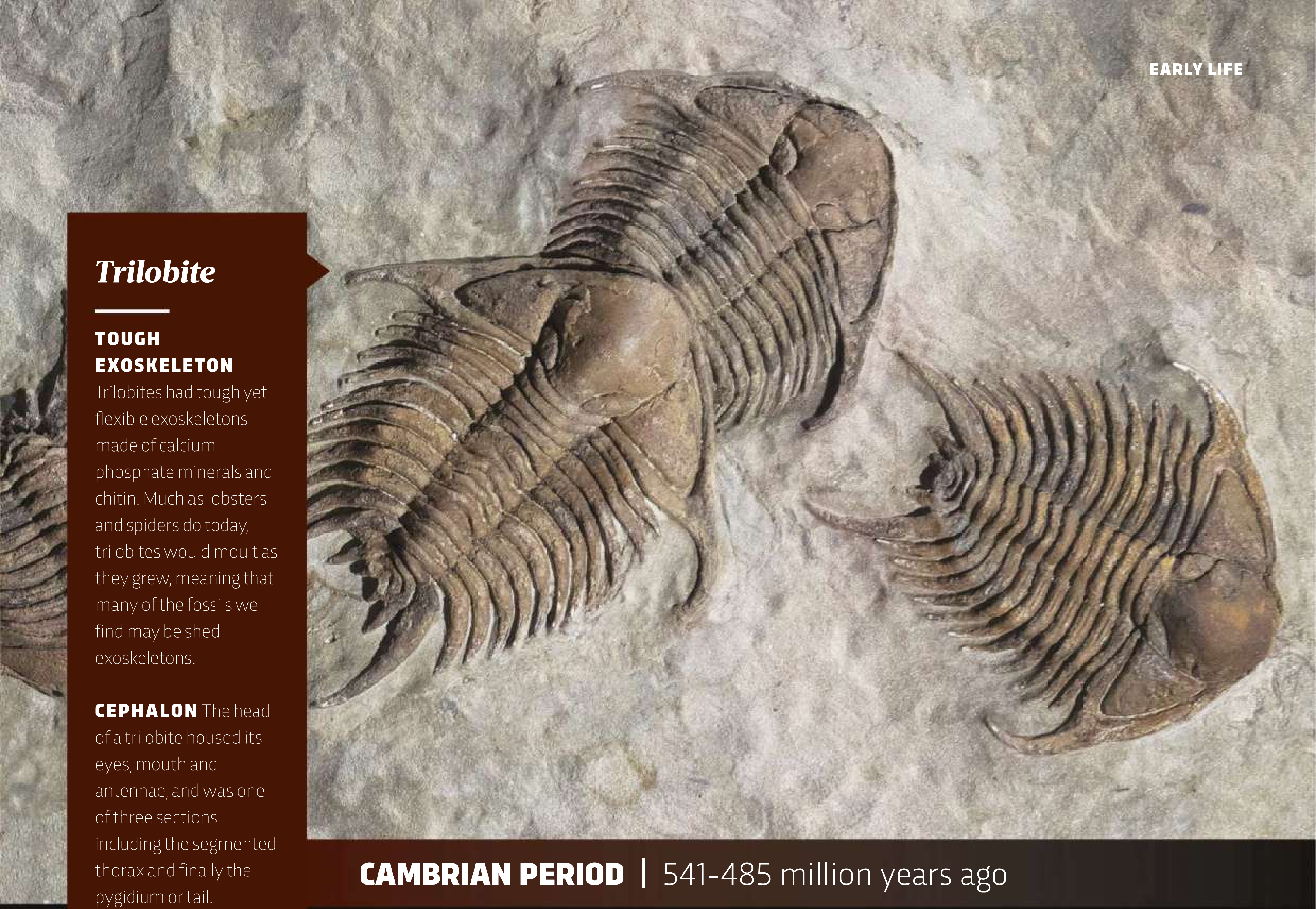


Trilobite

TOUGH EXOSKELETON Trilobites had tough yet flexible exoskeletons made of calcium phosphate minerals and chitin. Much as lobsters and spiders do today, trilobites would moult as they grew, meaning that many of the fossils we find may be shed exoskeletons.

CEPHALON The head of a trilobite housed its eyes, mouth and antennae, and was one of three sections including the segmented thorax and finally the pygidium or tail.

COMPOUND EYES Trilobites' vision was excellent and they had some of the first complex compound eyes in the fossil record, each with up to 15,000 polygonal lenses made of calcite.

TUBERCULES Bumps on the surface of exoskeletons, noticeable on the cephalon of many trilobites, may have been used as sensory organs, defence structures, camouflage or to create grip for digging.

SPINES Many trilobites had sharp defensive spines.

CAMBRIAN PERIOD | 541-485 million years ago

HARD SHELLS

PRIOR TO THE discovery of the Ediacarans in 1946, all complex animal life was thought to have burst into existence about 541 million years ago in an event dubbed the Cambrian Explosion.

We now know that animals had started eating one another and digging into the seafloor in search of food, so worm burrows and hard defences, such as shells and spines, meant they were suddenly far more likely to fossilise.

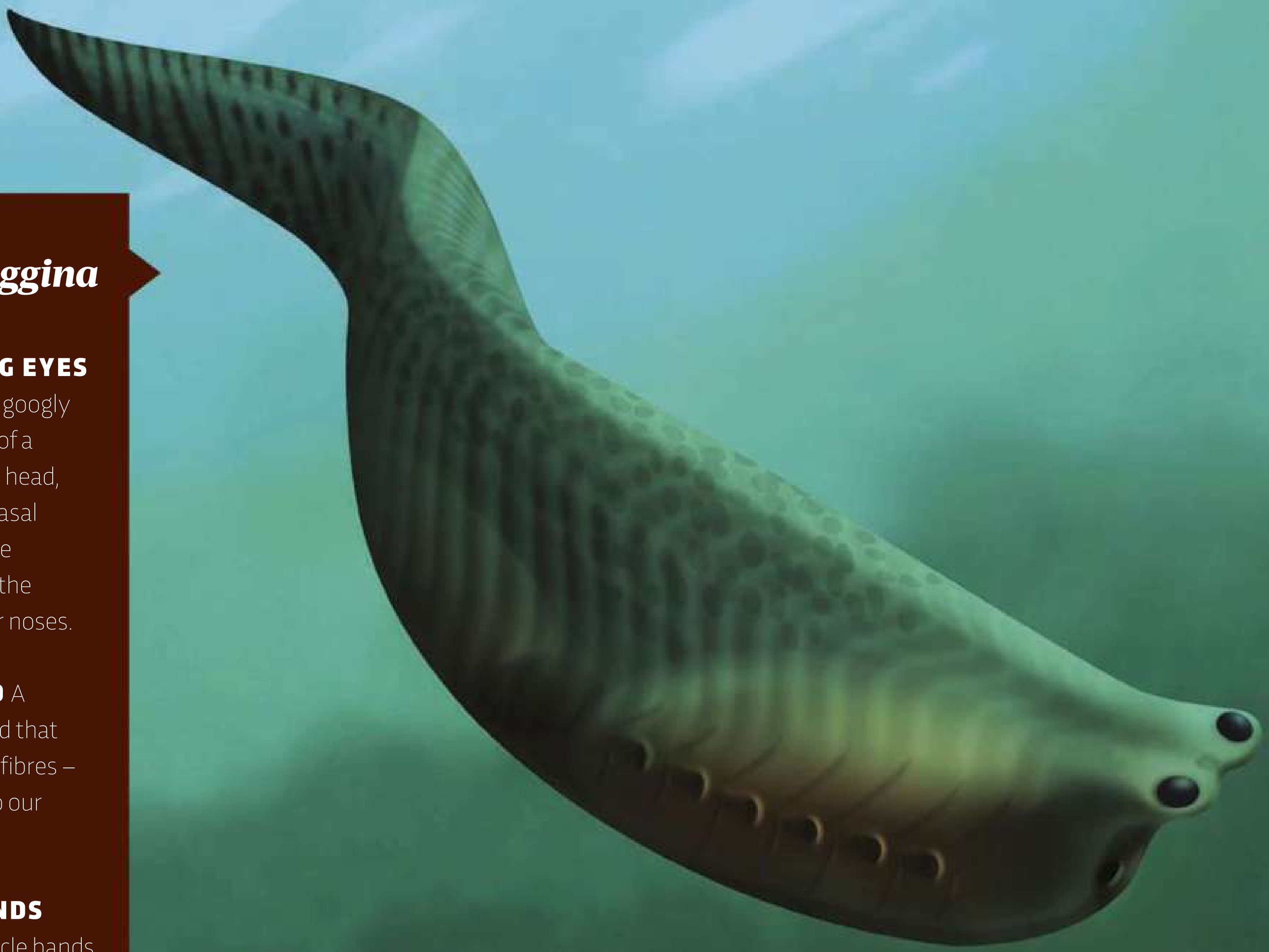
The first species with a hint of a backbone, molluscs, arthropods, sponges, worms, echinoderms (such as starfish) and many other groups are all found as fossils at this time.

One group of early animals that took the development of hard defences to the extreme were trilobites, the oldest of which are about 520 million years old. More than 50,000 species of trilobites have been found as fossils, and they are covered in a wide array of spikes and spines.

Did you know?

Trilobites are one of the most successful groups of animals ever. They survived for more than 250 million years and were widespread globally. The last disappeared in a mass extinction at the end of the Permian Period, 252 million years ago, along with 95 per cent of all marine species.

Anomalocaris (left) has been described as the great white shark of the Cambrian and Ordovician seas. This relative of arthropods grew to 1m in length, swam using undulating lobes on its sides and had two spiked arms to snatch prey into its mouth.



Metaspriggina

PROTRUDING EYES *Metaspriggina*'s googly eyes were part of a well-developed head, also featuring nasal sacs to sense the environment – the precursor to our noses.

NOTOCHORD A cartilaginous rod that supports nerve fibres – the precursor to our spine.

MUSCLE BANDS W-shaped muscle bands along *Metaspriggina*'s body hint it was a good swimmer. It either had no fins or they didn't fossilise.

GILL ARCHES *Metaspriggina* had seven pairs of external gill arches with which it extracted oxygen from the water, a feature it shares with later jawed fish.

TAIL A tail that is an extension of the body and continues past the anal opening is another feature shared with all chordates.

CAMBRIAN PERIOD | 541-485 million years ago

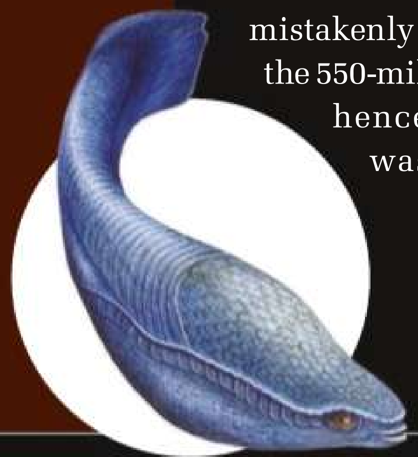
FIRST VERTEBRATES

CHORDATES – CREATURES WITH simple cords of nerve fibres running down their 'backs' – were one of the animals to appear during the Cambrian Explosion. One of the first vertebrates and earliest fish was a creature called *Metaspriggina*, which evolved around 505 million years ago.

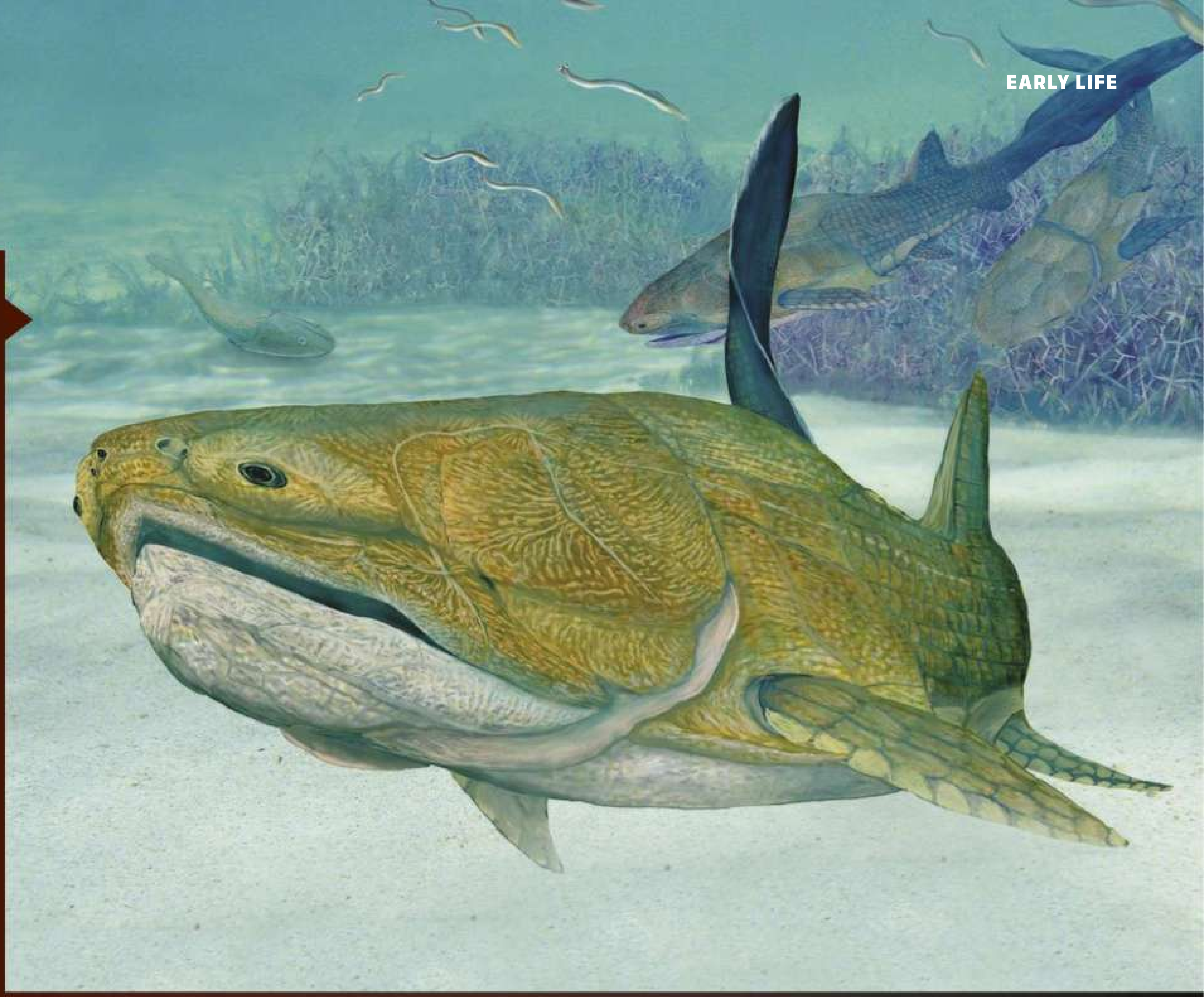
When first described, it was mistakenly believed to be related to the 550-million-year-old *Spriggina*, hence its name. But that was rectified with more Burgess Shale fossil discoveries. This 6cm-long, jawless fish looked unlike fish today, although it had protruding eyes, breathed through gills and had a 'notochord' – a stiff rod of cartilage supporting nerves and bands of muscle along its body. Those muscles made it a fast swimmer and helped it evade Cambrian predators such as *Anomalocaris*. Though it was yet to develop mineralised bones, it was well on the way to becoming a vertebrate.

Did you know?

The first vertebrates on Earth evolved in shallow coastal waters, no more than 60 metres deep. For almost 100 million years, these creatures continued to develop in this environment, evolving different characteristics, such as armoured or streamlined bodies.



A 480-million-year-old fish called *Arandaspis* (left) was one of the first to have bony armour plates in its skin, which are thought to have been the precursors to the vertebrate skeleton. This 20cm-long fish lived in the Larapintine Sea during the Ordovician Period.



Entelognathus

COMPLEX JAW
Entelognathus' jaw had a complex arrangement of small bones, similar to bony fish today. These included the dentary (our lower jaw) and the premaxilla and maxilla (our upper jaw).

ARMOURED HEAD AND BODY
Placoderms had bony plates on their heads and bodies, with an unusual joint between the head and neck that allowed for movement.

INTERNAL EAR
Placoderms were the first vertebrates to have three semi-circular canals in their ears for balance, a feature that we still have today.

BONY EYES
Even the eyes of placoderms were fitted with bony plates, suggesting that the arms race between predators and prey had really got into its stride during the Silurian period.

SCALES
The rear of the body and tail were covered in scales and were relatively unprotected.

SILURIAN PERIOD | 443-419 million years ago

FIRST BITING JAWS

THE EARLIEST FISH, such as *Metaspriggina*, had to suck up their food. But the evolution of hard jaws with which to grip and crush shells and exoskeletons opened a whole new evolutionary space to explore, and enabled these fish to hunt bigger, more challenging prey.

Placoderm fish, which were covered in bony armour plates, were the first vertebrates with well-developed pelvic fins and jaws. They are thought to have appeared around 440 million years ago in the Silurian Period and had simple, beak-like jaws made of bony plates. By 419 million years ago a fish called *Entelognathus* (which means 'complete jaw') had appeared and had a complex set of bones in its lower jaw, including a 'dentary' bone that is found today in bony fish, amphibians, reptiles and mammals. The 20cm-long *Entelognathus* is perhaps the first animal to have had what we would recognise as a face.

380 million years ago in the late Devonian Period, *Dunkleosteus (left)*, a 6m-long fish was the apex predator of the seas. The great white shark-sized armoured placoderm chomped down on other sharks with self-sharpening bony blades for jaws.

Did you know?

Placoderms were the first animals to have sexual intercourse, rather than laying eggs and fertilising them outside the body. The external genitalia of males were paired appendages called 'bony claspers', which they used to deposit sperm inside the females.

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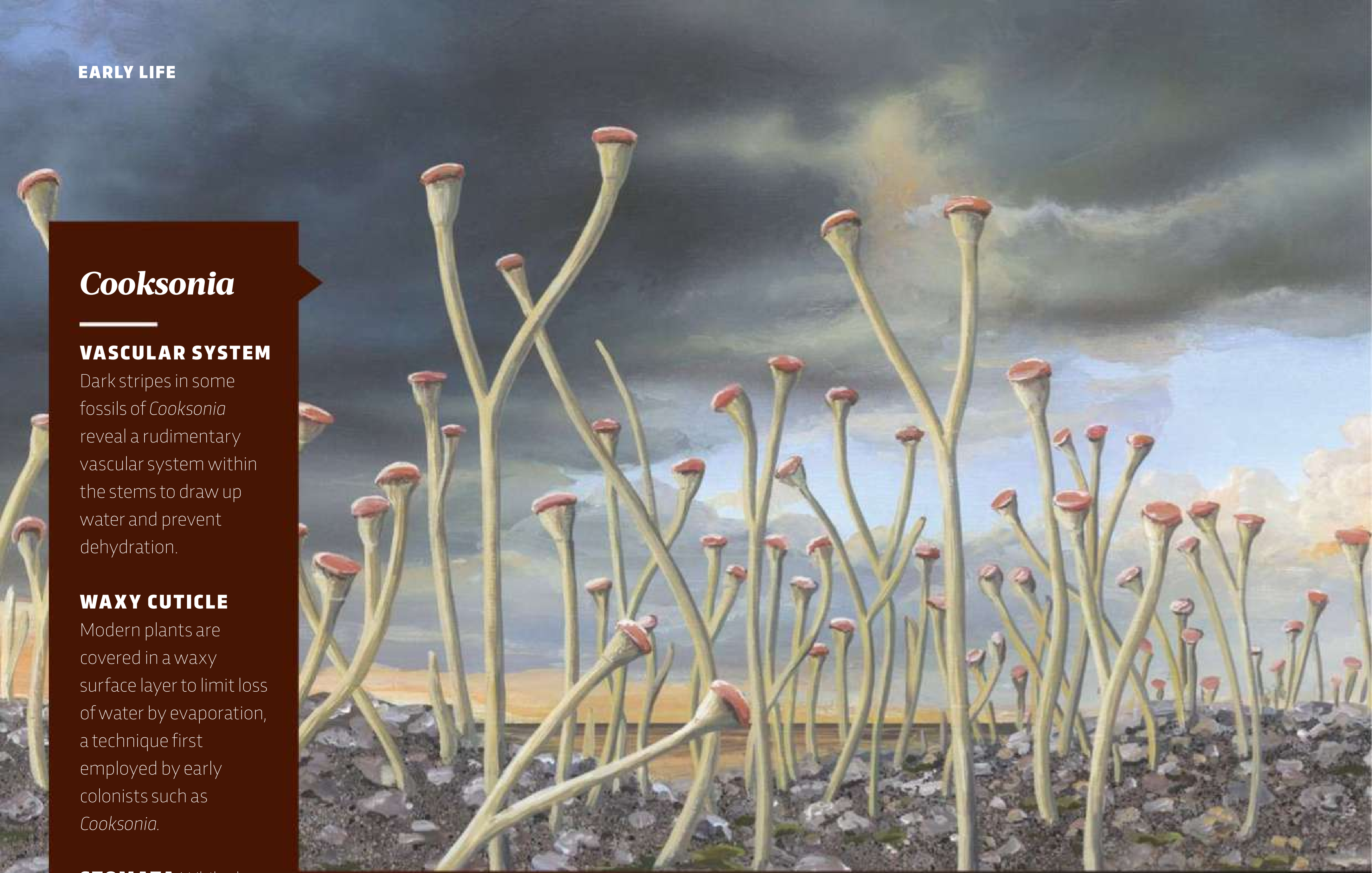

Cooksonia

VASCULAR SYSTEM Dark stripes in some fossils of *Cooksonia* reveal a rudimentary vascular system within the stems to draw up water and prevent dehydration.

WAXY CUTICLE Modern plants are covered in a waxy surface layer to limit loss of water by evaporation, a technique first employed by early colonists such as *Cooksonia*.

STOMATA While the cuticle prevents evaporation, it also stops the plant drawing in oxygen and carbon dioxide, *Cooksonia* had pores called stomata to allow transfer of gases with its tissues.

SPORANGIUM Trumpet-shaped knobs on the end of each branching stem where spore-bearing capsules, used to spread the next generation of botanical colonists.

SILURIAN PERIOD | 443-419 million years ago

FIRST LAND PLANTS

WHILE LIFE WAS already thriving in the oceans half a billion years ago, Earth's land remained a relative biological desert. Following in the footsteps of photosynthetic microbes and lichen, simple land plants made the transition from water to land about 500 million years ago, genetic studies suggest, while fossilised spores from moss and liverwort-like plants have been dated to about 470 million years ago.

One of the earliest known vascular plants was *Cooksonia*, which evolved around 425 million years ago. For at least 40 million years it would have been vascular plants like this that dominated Earth's surface, enriching and stabilising soils, and oxygenating the atmosphere.

Around 370 million years ago, there was an explosion in different plant types, including early trees with wood. These plants had roots and leaves, and included ferns and early ancestors of gymnosperms (cycads, ginkgo, yews and conifers).

The most successful land plants today, with around 370,000 known species are the flowering plants of angiosperms. The earliest known fossil angiosperm is 130-million-year-old *Montsechia*, described from Spain in 2015.

BBC TWO

*Watch clips of David Attenborough's series **First Life** bbc.in/2X8Bsrk*

by JOHN PICKRELL
(@john_pickrell)
*John is a Sydney-based writer and the author of **Flying Dinosaurs** and **Weird Dinosaurs.***

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Ichthyostega

TAIL *Ichthyostega*'s tail had a small fin and a series of bony supports similar to those in ray-finned fish. It may have allowed *Ichthyostega* to swim by propelling it through the water.

HIND LIMBS Unlike all modern tetrapods, which have five toes on each foot (except those that have secondarily lost them), *Ichthyostega* had seven toes on each of its hind limbs.

FORELIMBS *Ichthyostega*'s squat forelimbs were larger and more powerful than its hindlimbs and were useful for hauling it up out of the water.

HEAD A wide skull with eyes on top of the head may have allowed it to look upwards through the water while on the hunt for prey.

DEVONIAN PERIOD | 419-358 million years ago

FIRST TETRAPODS

PLANTS WERE FLOURISHING, and invertebrates had already invaded Earth's terrestrial environments, by the time vertebrates were ready to fully venture onto land. The first was perhaps something like the 1.5m-long *Ichthyostega*, discovered in 1929 in the 370-million-year-old late Devonian rocks of eastern Greenland. This four-limbed semi-aquatic creature is thought to be closely related to the ancestor of all tetrapods (four-legged animals and all their descendants, including amphibians, reptiles, birds and mammals).

Despite having lungs to breath air, *Ichthyostega* retained a number of features of its ancestors, such as scales and skull bones which form the gill covers in some fish. It may have used its limbs and lungs to help it manoeuvre through swampy environments, possibly brackish deltas and estuaries. But it was likely not a great walker, and dragged itself on land like a seal rather than a salamander.

Titaalik (375 million years old) was even more like the lobe-finned fish (such as living coelacanths) from which tetrapods evolved. It still had gills and fins, and spent most of its time in water, but also had primitive limb bones, which it may have used to prop itself up in the shallows.

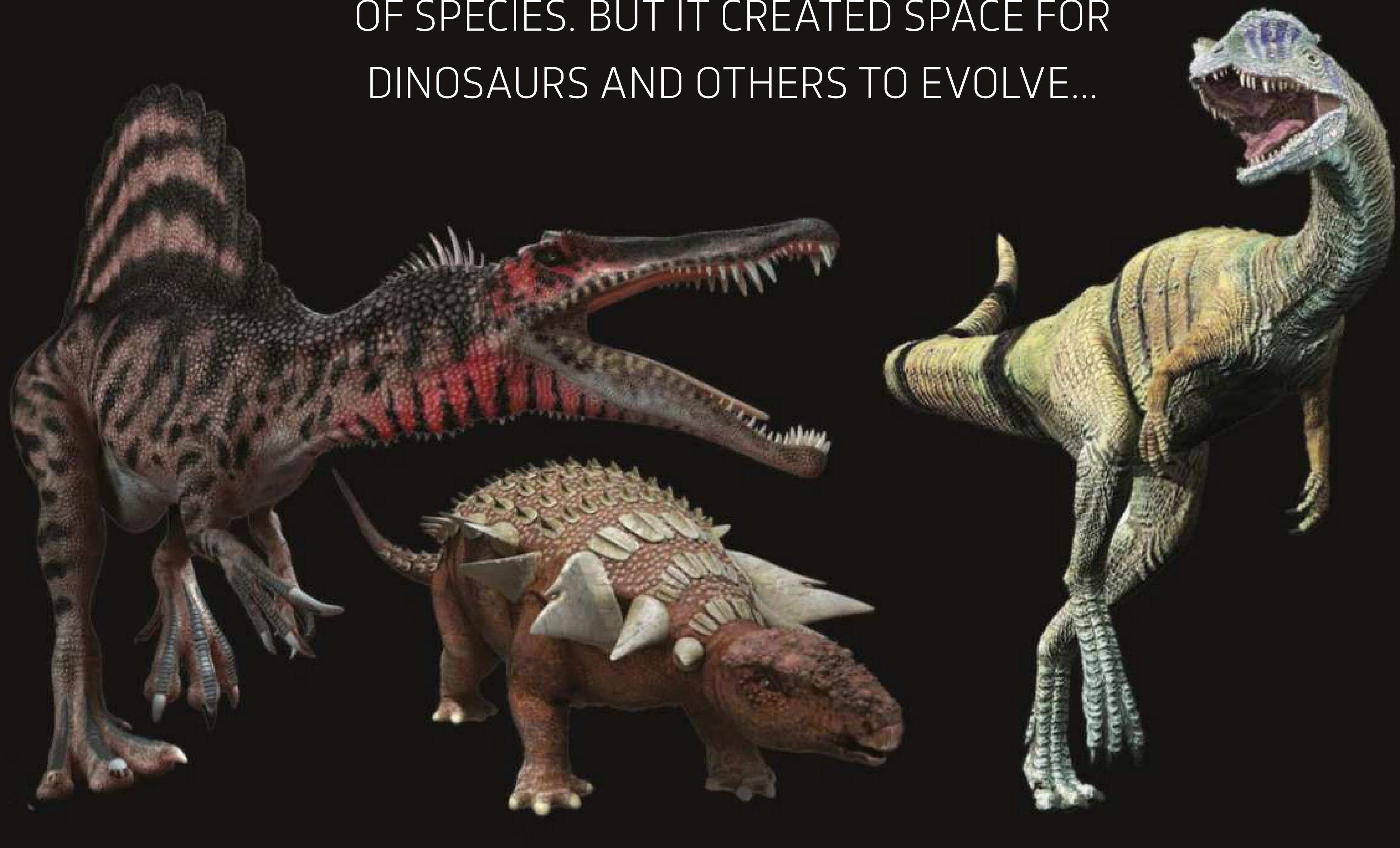
Did you know?

Dozens of footprints left by a tetrapod 395 million years ago, and revealed from a fossil site in Poland, show that amphibious creatures similar to *Ichthyostega* must have already been on land at least 20 million years earlier than the fossil bones suggest.

DINOSAUR

THE MESOZOIC ERA
252 - 66 MILLION YEARS AGO

THE PERMIAN-TRIASSIC MASS EXTINCTION EVENT, 252 MILLION YEARS AGO, WAS THE WORST EXTINCTION EVENT OF ALL TIME, KILLING UP TO 96 PER CENT OF SPECIES. BUT IT CREATED SPACE FOR DINOSAURS AND OTHERS TO EVOLVE…



EVOLUTION

Early Triassic
252-246 MYA

Mid Triassic
246-229 MYA

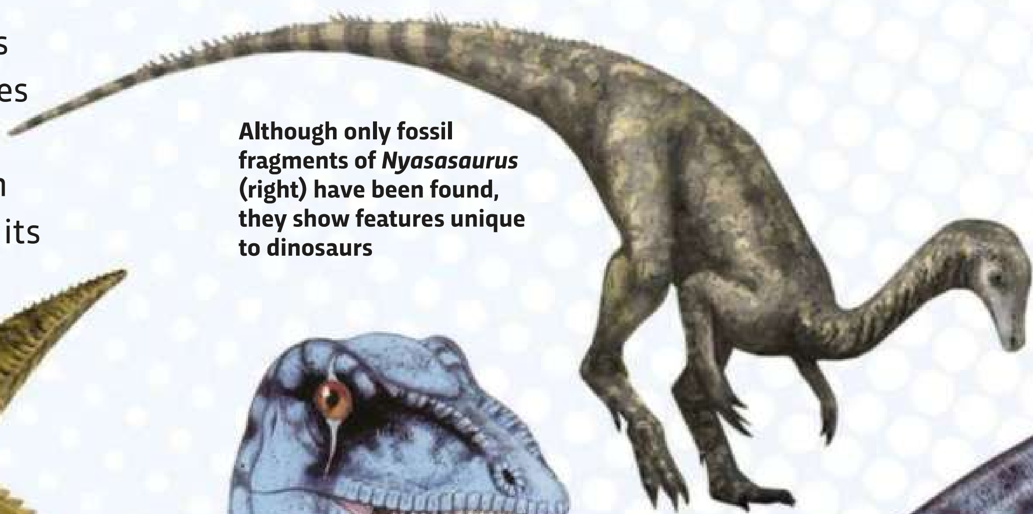
Late Triassic
229-200 MYA

245 MYA
DINOSAUR ANCESTORS

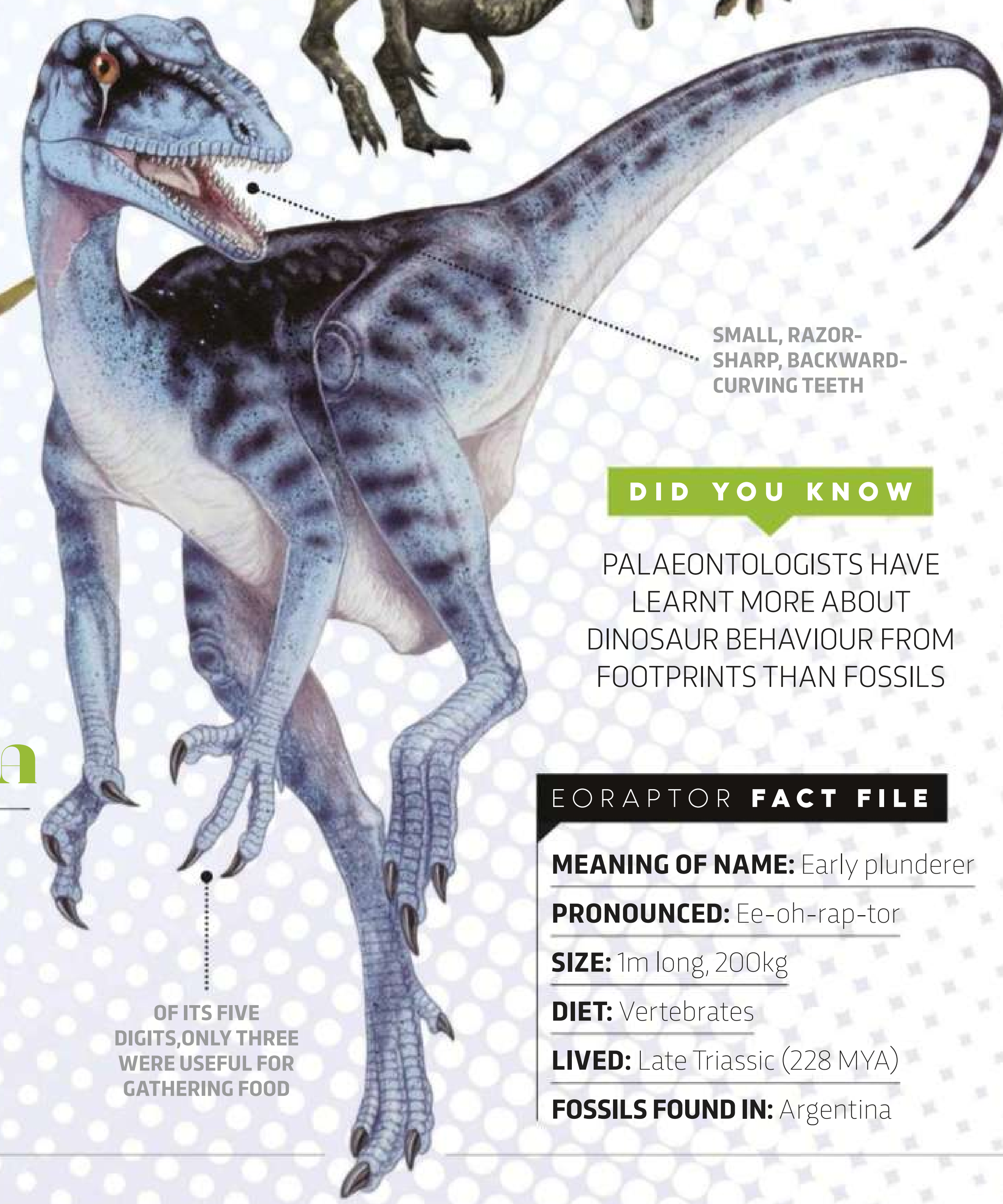
Archosaurs ('ruling reptiles') evolved around 245 million years ago. They are the ancestors of dinosaurs and pterosaurs (flying reptiles) as well as modern-day crocodiles and birds. *Desmatosuchus* (below) was a herbivore with an armoured body that used its long spikes for self-defence.

243 MYA
FIRST DINOSAUR

The dog-sized *Nyasasaurus* (below) is either the oldest known dinosaur or the closest known relative to the earliest dinosaurs, preceding any other dinosaur by 12 million years.



Although only fossil fragments of *Nyasasaurus* (right) have been found, they show features unique to dinosaurs



DID YOU KNOW

PALAEONTOLOGISTS HAVE LEARNT MORE ABOUT DINOSAUR BEHAVIOUR FROM FOOTPRINTS THAN FOSSILS

231-228 MYA
EORAPTOR

WAS ONE OF THE FIRST DINOSAURS. Its hands had five digits, but two of these were clawless stumps. Only juveniles have been found so far.

EORAPTOR **FACT FILE**

MEANING OF NAME: Early plunderer
PRONOUNCED: Ee-oh-rap-tor
SIZE: 1m long, 200kg
DIET: Vertebrates
LIVED: Late Triassic (228 MYA)
FOSSILS FOUND IN: Argentina

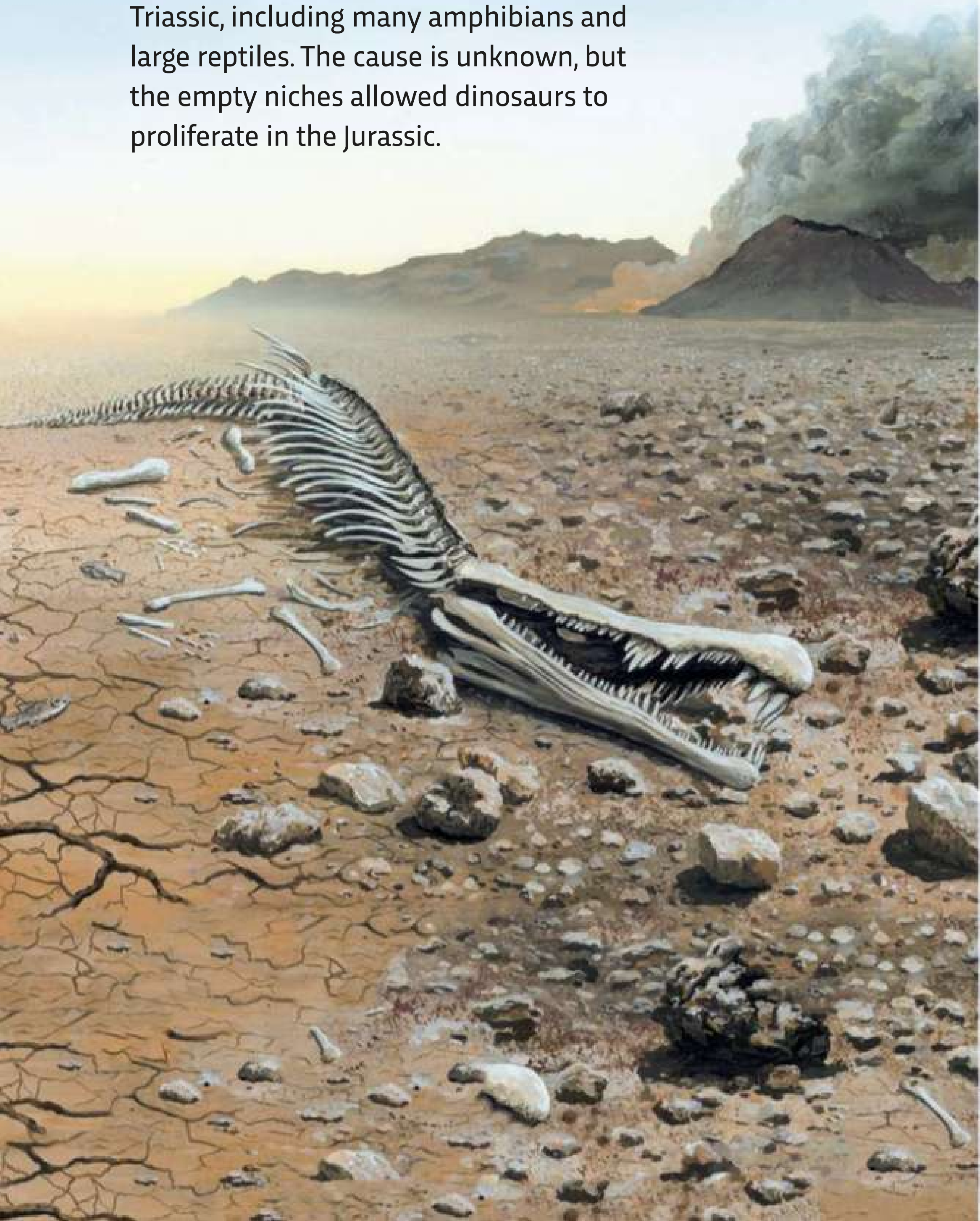
214 MYA
PLATEOSAURUS

(left) lived in herds. Graveyards, where more than 55 individuals are preserved together, show where they became stuck in the mud and starved to death.

The shrew-like *Juramaia sinensis* (above) is thought to have been the earliest 'true' mammal

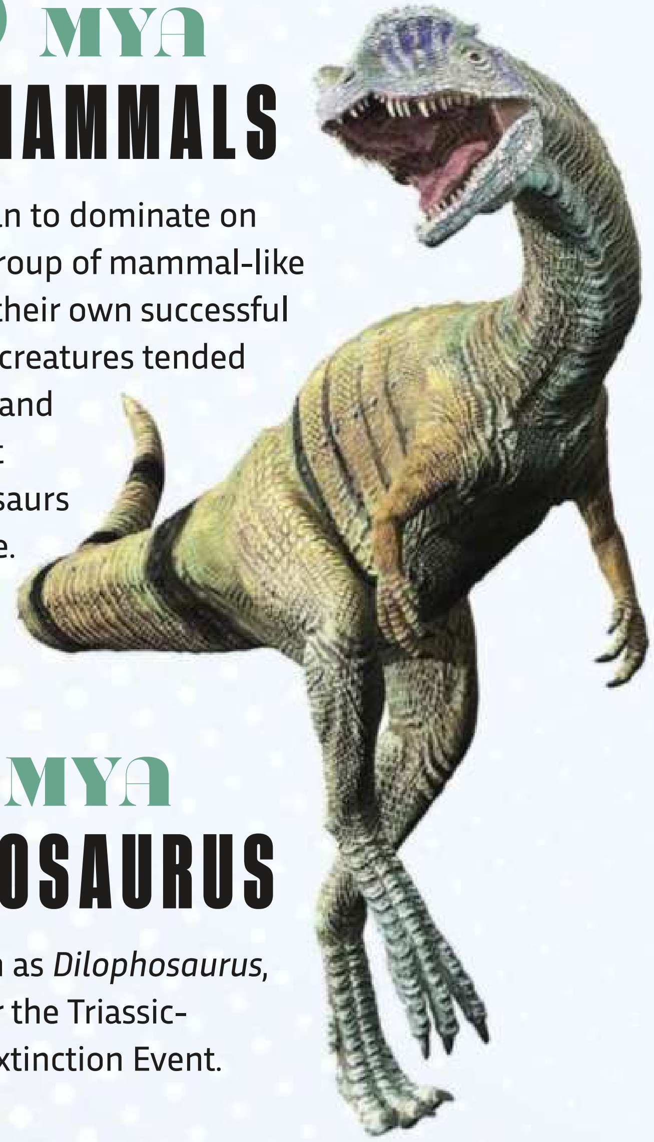
201 MYA
TRIASSIC-JURASSIC
Mass extinction event

Between 70 and 75 per cent of Earth's species went extinct at the end of the Triassic, including many amphibians and large reptiles. The cause is unknown, but the empty niches allowed dinosaurs to proliferate in the Jurassic.



200 MYA
FIRST MAMMALS

Dinosaurs began to dominate on land, but one group of mammal-like reptiles found their own successful niche. The tiny creatures tended to live in trees, and hunted at night when the dinosaurs were less active.

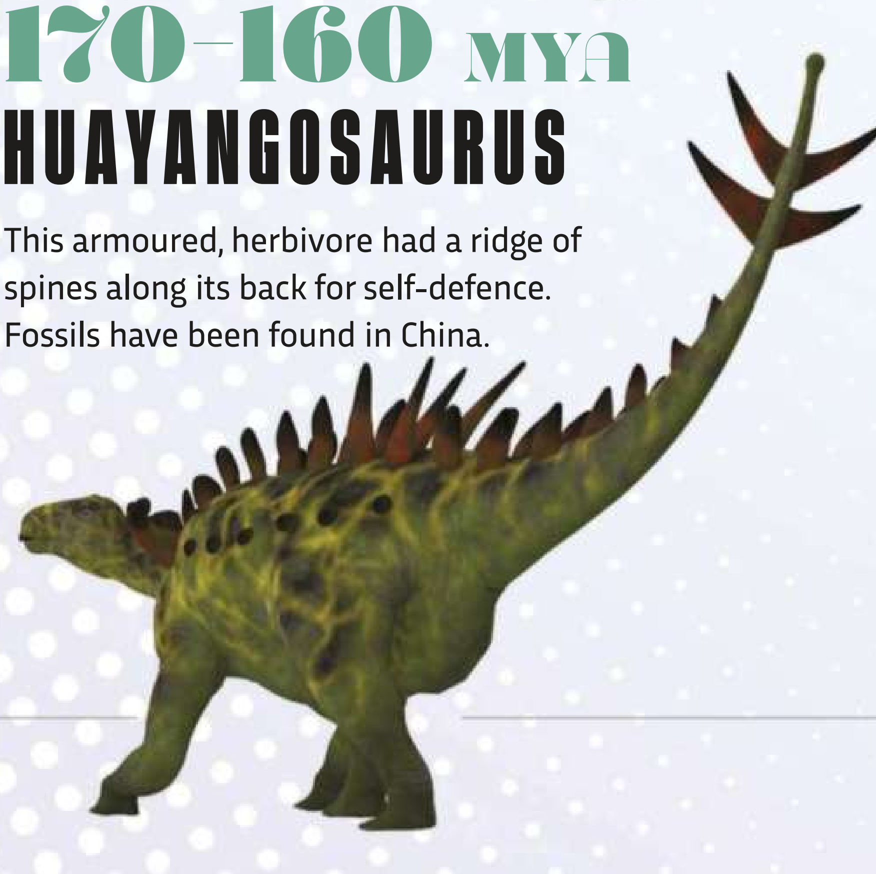


190 MYA
DILOPHOSAURUS

Dinosaurs, such as *Dilophosaurus*, prospered after the Triassic-Jurassic Mass Extinction Event.

170-160 MYA
HUAYANGOSAURUS

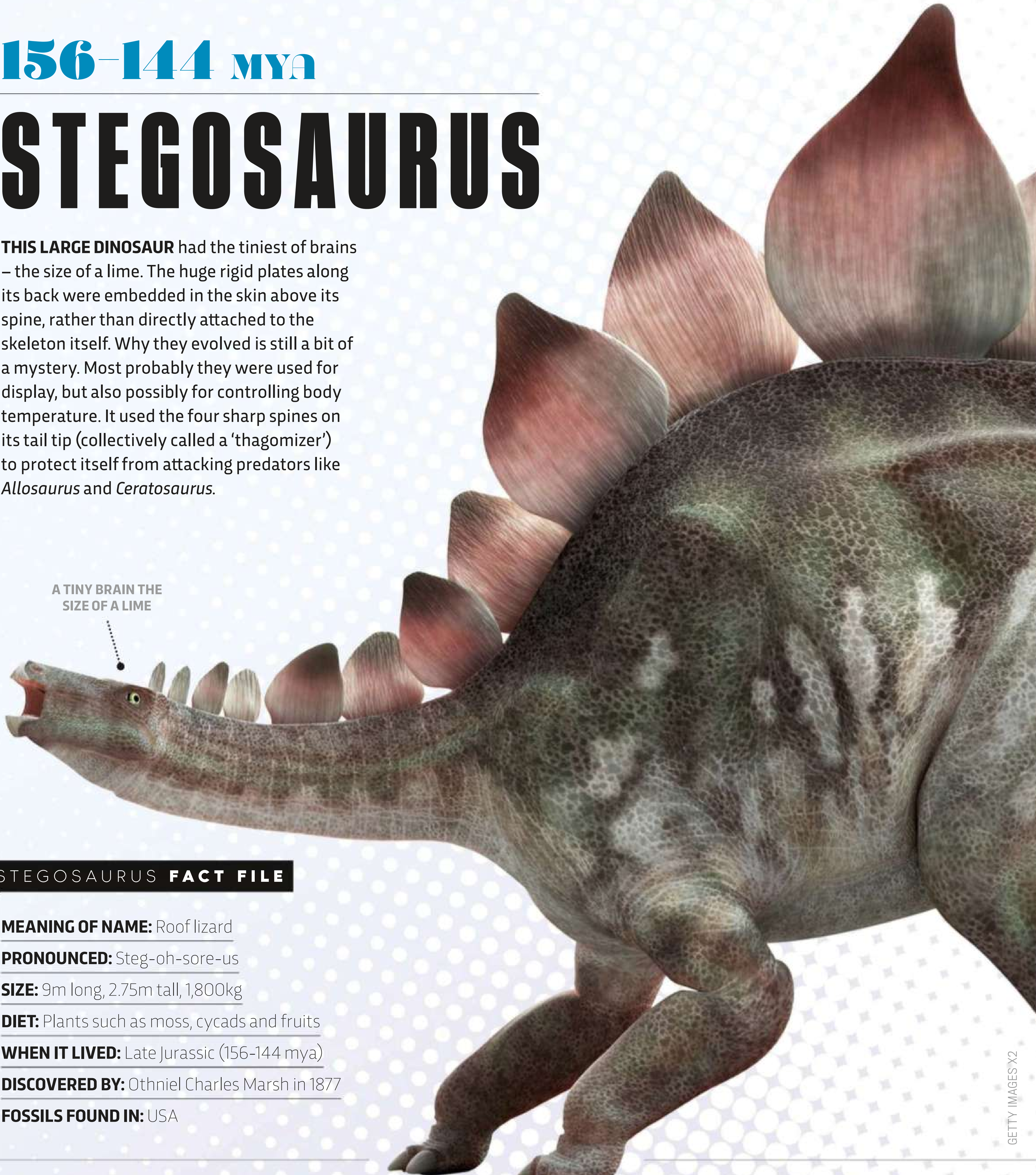
This armoured, herbivore had a ridge of spines along its back for self-defence. Fossils have been found in China.



156-144 MYA

STEGOSAURUS

THIS LARGE DINOSAUR had the tiniest of brains – the size of a lime. The huge rigid plates along its back were embedded in the skin above its spine, rather than directly attached to the skeleton itself. Why they evolved is still a bit of a mystery. Most probably they were used for display, but also possibly for controlling body temperature. It used the four sharp spines on its tail tip (collectively called a 'thagomizer') to protect itself from attacking predators like *Allosaurus* and *Ceratosaurus*.



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STEGOSAURUS **FACT FILE**

MEANING OF NAME: Roof lizard

PRONOUNCED: Steg-oh-sore-us

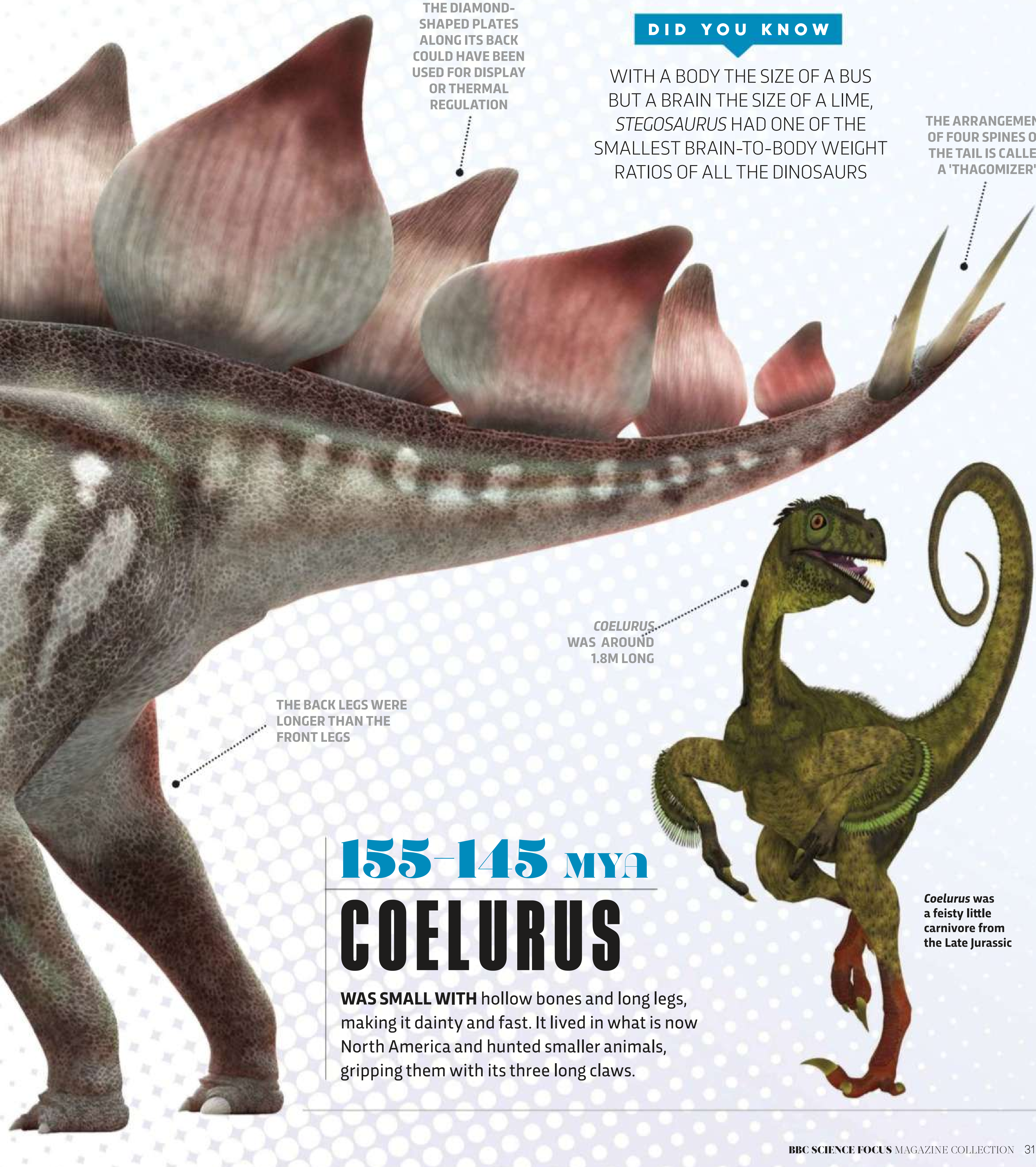
SIZE: 9m long, 2.75m tall, 1,800kg

DIET: Plants such as moss, cycads and fruits

WHEN IT LIVED: Late Jurassic (156-144 mya)

DISCOVERED BY: Othniel Charles Marsh in 1877

FOSSILS FOUND IN: USA



DID YOU KNOW

WITH A BODY THE SIZE OF A BUS BUT A BRAIN THE SIZE OF A LIME, *STEGOSAURUS* HAD ONE OF THE SMALLEST BRAIN-TO-BODY WEIGHT RATIOS OF ALL THE DINOSAURS

Coelurus was a feisty little carnivore from the Late Jurassic

155-145 MYA

COELURUS

WAS SMALL WITH hollow bones and long legs, making it dainty and fast. It lived in what is now North America and hunted smaller animals, gripping them with its three long claws.

DID YOU KNOW

BRACHIOSAURUS HAD WIDE JAWS AND COULD TAKE HUGE MOUTHFULS OF FOOD WITH EVERY BITE, WHICH WERE MOSTLY SWALLOWED WHOLE

155-140 MYA

BRACHIOSAURUS

DESPITE THE NECK of this mighty, Late Jurassic herbivore being its defining feature, *Brachiosaurus* means 'arm lizard'. Due to its colossal size and herbivorous diet, it had to eat a whopping 400kg every day. Once thought to have made its home in water because of the high position of its bony nostril openings, it is now understood that it had nostrils close to the front of its snout and, hence, lived on land. It probably roamed in herds in dry, park-like environments.

BRACHIOSAURUS **FACT FILE**

MEANING OF NAME: Arm lizard

PRONOUNCED: Brak-ee-oh-sore-us

SIZE: 30m long, 7m tall at shoulder, 5,500kg

DIET: Tall vegetation

WHEN IT LIVED: Late Jurassic (155-140 MYA)

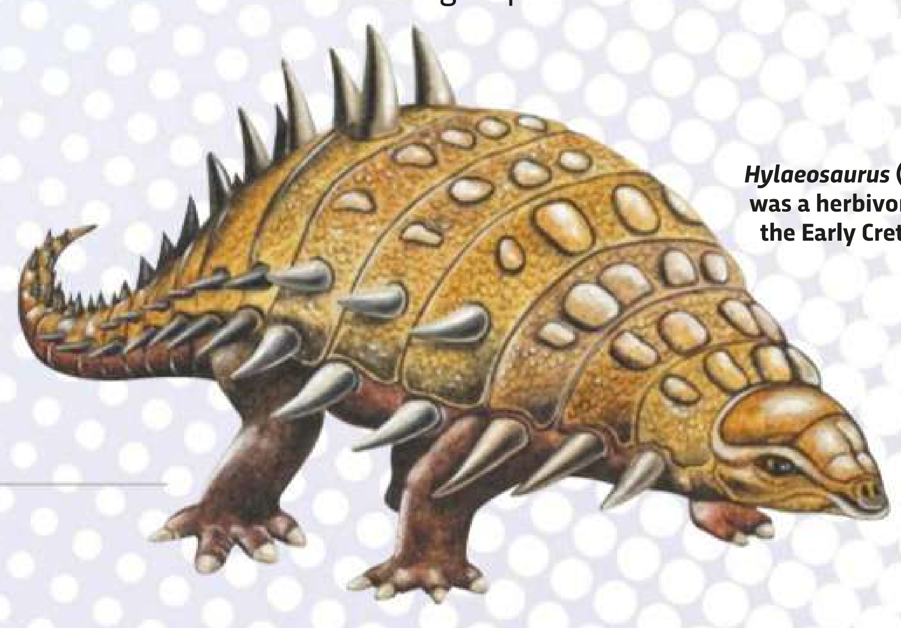
DISCOVERED BY: Elmer Riggs in 1900

FOSSILS DISCOVERED IN: USA, Portugal, Algeria, Tanzania

150-135 MYA

HYLAEOSAURUS

was one of the first three fossils that led Victorian scientist Richard Owen to realise that certain fossil reptiles represented a brand new group – dinosaurs.



***Hylaeosaurus* (below) was a herbivore from the Early Cretaceous**

147 MYA

ARCHAEOPTERYX

GETTY IMAGES X3

WAS A SMALL, carnivorous bird-like dinosaur, weighing just 500g, which lived during the Late Jurassic. It has been described as the 'first bird' and the missing link between dinosaurs and birds.

DID YOU KNOW

ARCHAEOPTERYX'S CLAW STRUCTURE SUGGESTS IT DIDN'T OFTEN CLIMB TREES IN ORDER TO GLIDE, YET IT HAD A PRIMITIVE SHOULDER GIRDLE THAT LIMITED ITS ABILITY TO FLAP ITS WINGS. SO IT PROBABLY JUST USED FLAPPING FLIGHT OVER SHORT DISTANCES

ARCHAEOPTERYX **FACT FILE**

MEANING OF NAME: Ancient wing

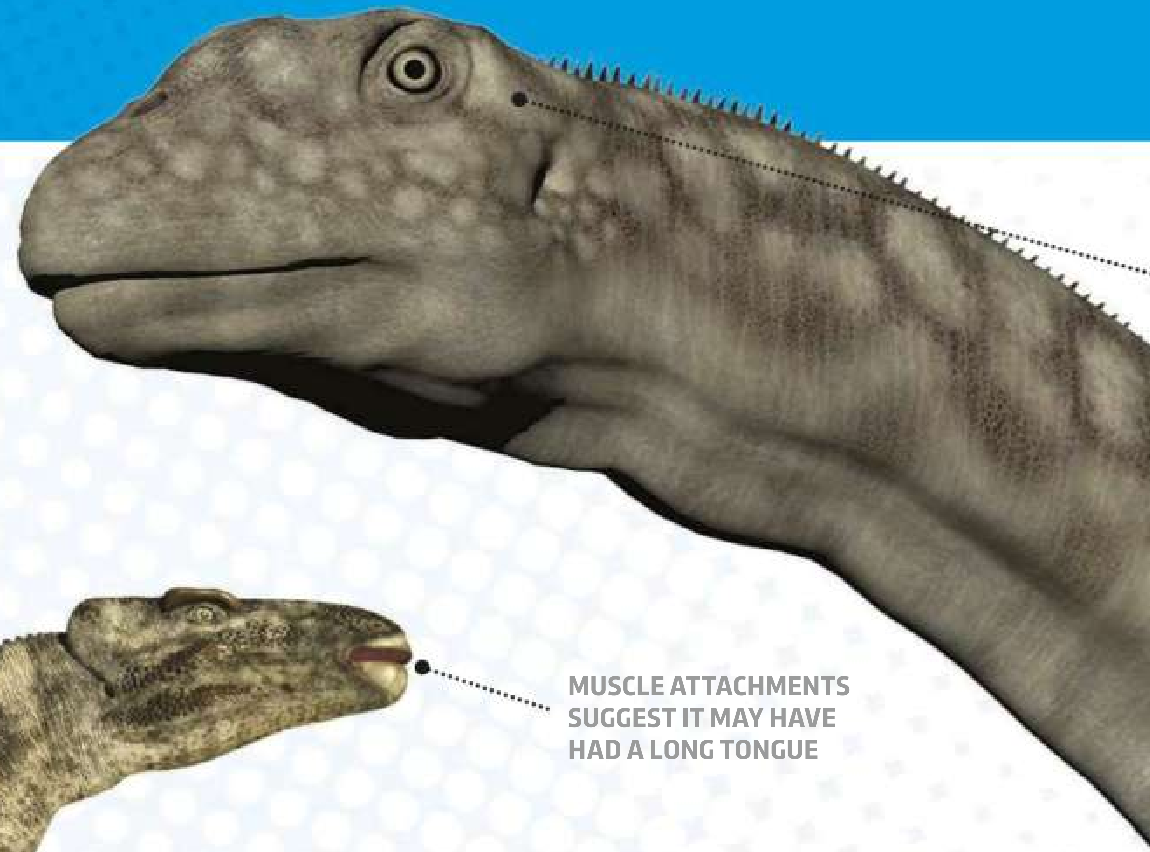
PRONOUNCED: Ark-ee-opt-er-ix

SIZE: 50cm long, 500g

DIET: Small reptiles, mammals or insects

WHEN IT LIVED: Late Jurassic (147 MYA)

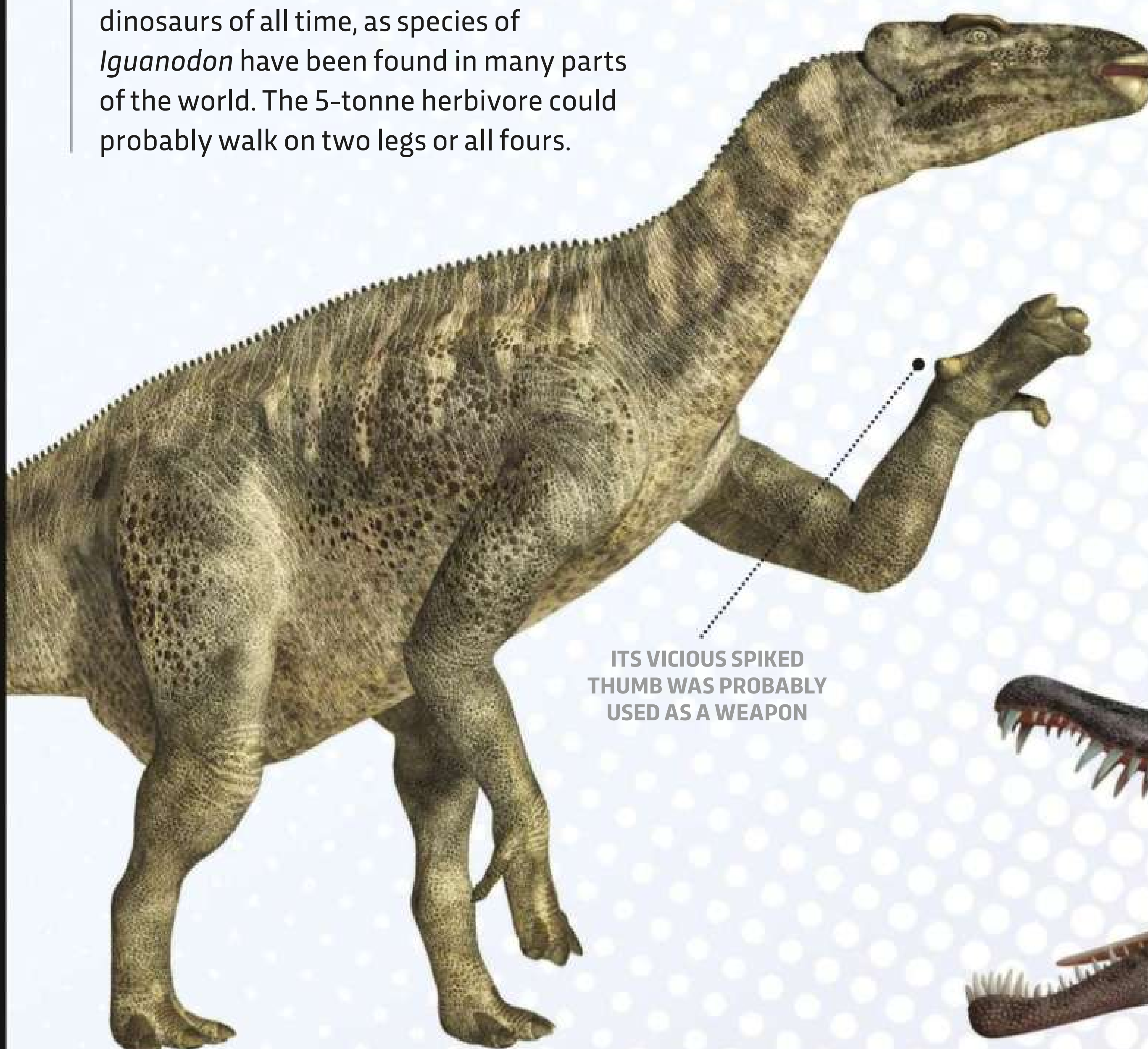
FOSSILS FOUND IN: Germany



135-125 MYA

IGUANODON

WAS ONE OF THE MOST successful dinosaurs of all time, as species of *Iguanodon* have been found in many parts of the world. The 5-tonne herbivore could probably walk on two legs or all fours.



MUSCLE ATTACHMENTS SUGGEST IT MAY HAVE HAD A LONG TONGUE

ITS VICIOUS SPIKED THUMB WAS PROBABLY USED AS A WEAPON

IGUANODON **FACT FILE**

MEANING OF NAME: Iguana tooth

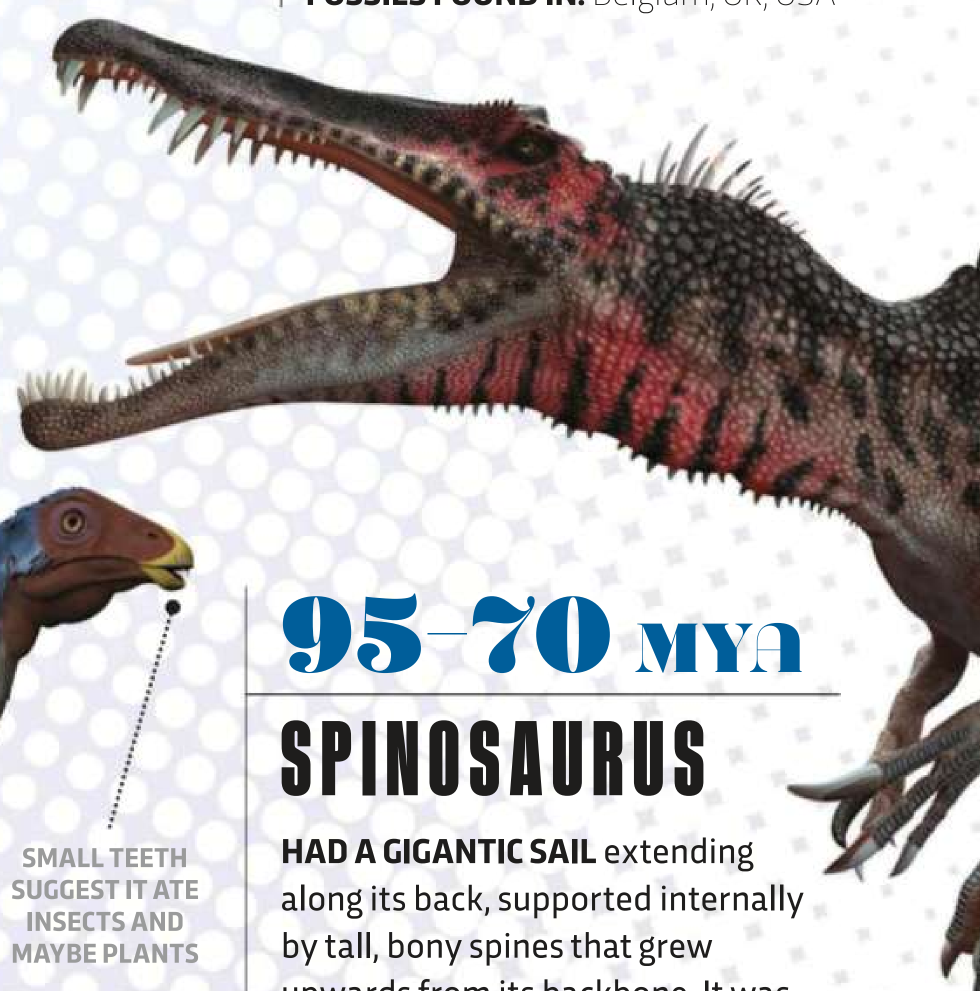
PRONOUNCED: Ig-wha-noh-don

SIZE: 10m long, 4,000kg

DIET: Vegetation

WHEN IT LIVED:
Early Cretaceous (140-110 MYA)

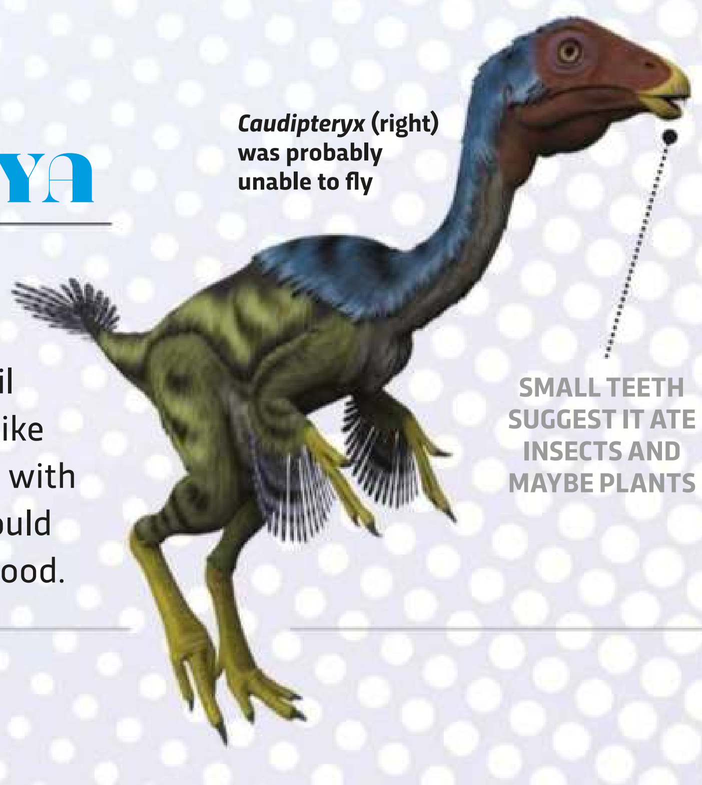
FOSSILS FOUND IN: Belgium, UK, USA



125-122 MYA

CAUDIPTERYX

HAD A FAN-LIKE ARRAY of large tail feathers, probably used in display like a peacock. Fossils have been found with small stones where its stomach would have been, perhaps to help digest food.



***Caudipteryx* (right) was probably unable to fly**

SMALL TEETH SUGGEST IT ATE INSECTS AND MAYBE PLANTS

95-70 MYA

SPINOSAURUS

HAD A GIGANTIC SAIL extending along its back, supported internally by tall, bony spines that grew upwards from its backbone. It was larger than *T. rex* but more slender.

ITS SMALL BRAIN RELATIVE TO ITS SIZE MEANT IT PROBABLY WASN'T THAT INTELLIGENT

90 MYA

ARGENTINOSAURUS

WAS THE HEAVIEST and longest land animal ever discovered, laying eggs the size of rugby balls. To fuel its huge size, it would have had to eat 100,000 calories a day – the equivalent of 2,127 apples.

ARGENTINOSAURUS **FACT FILE**

MEANING OF NAME: Argentina lizard

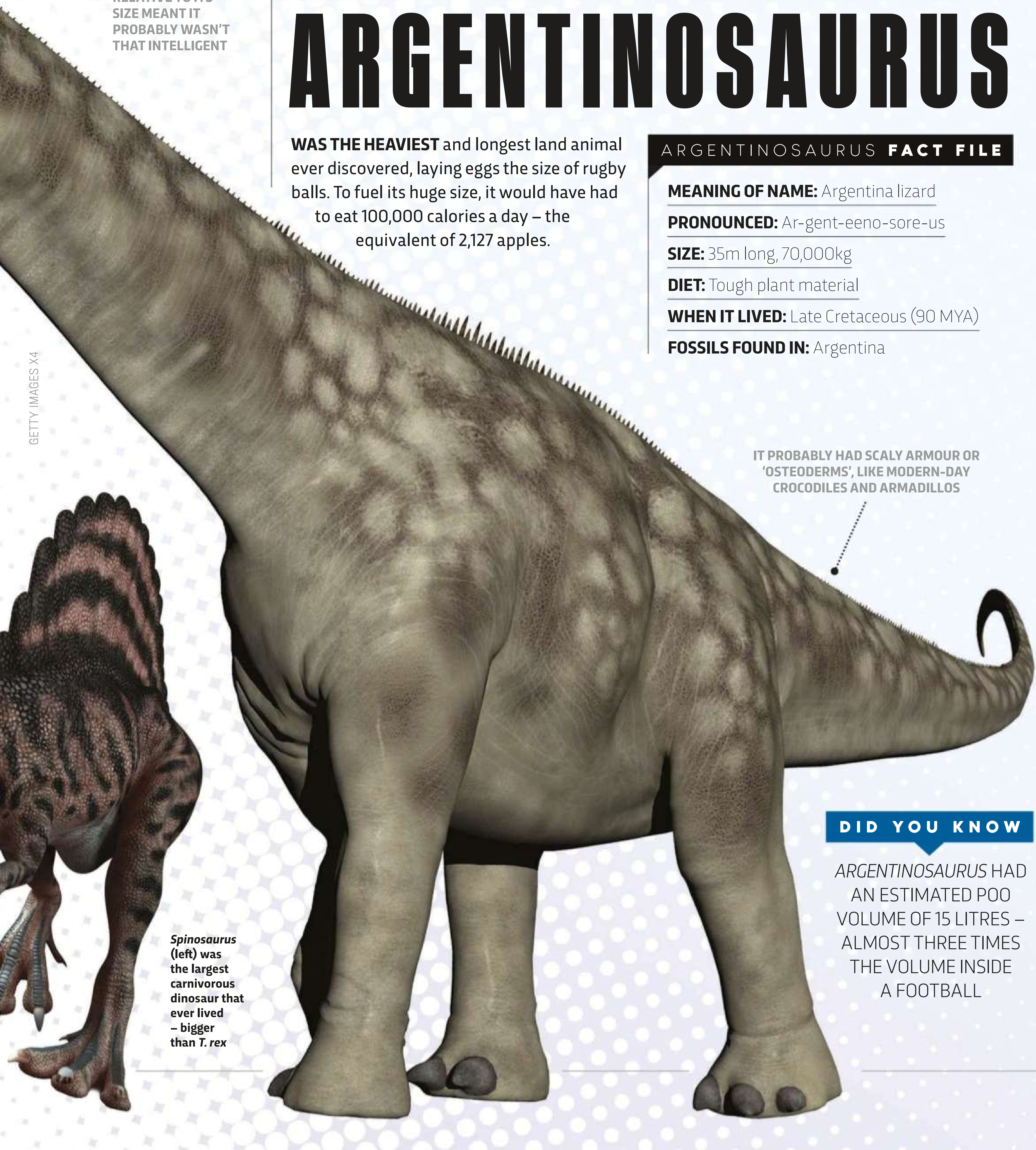
PRONOUNCED: Ar-gent-eeno-sore-us

SIZE: 35m long, 70,000kg

DIET: Tough plant material

WHEN IT LIVED: Late Cretaceous (90 MYA)

FOSSILS FOUND IN: Argentina



IT PROBABLY HAD SCALY ARMOUR OR 'OSTEODERMS', LIKE MODERN-DAY CROCODILES AND ARMADILLOS

DID YOU KNOW

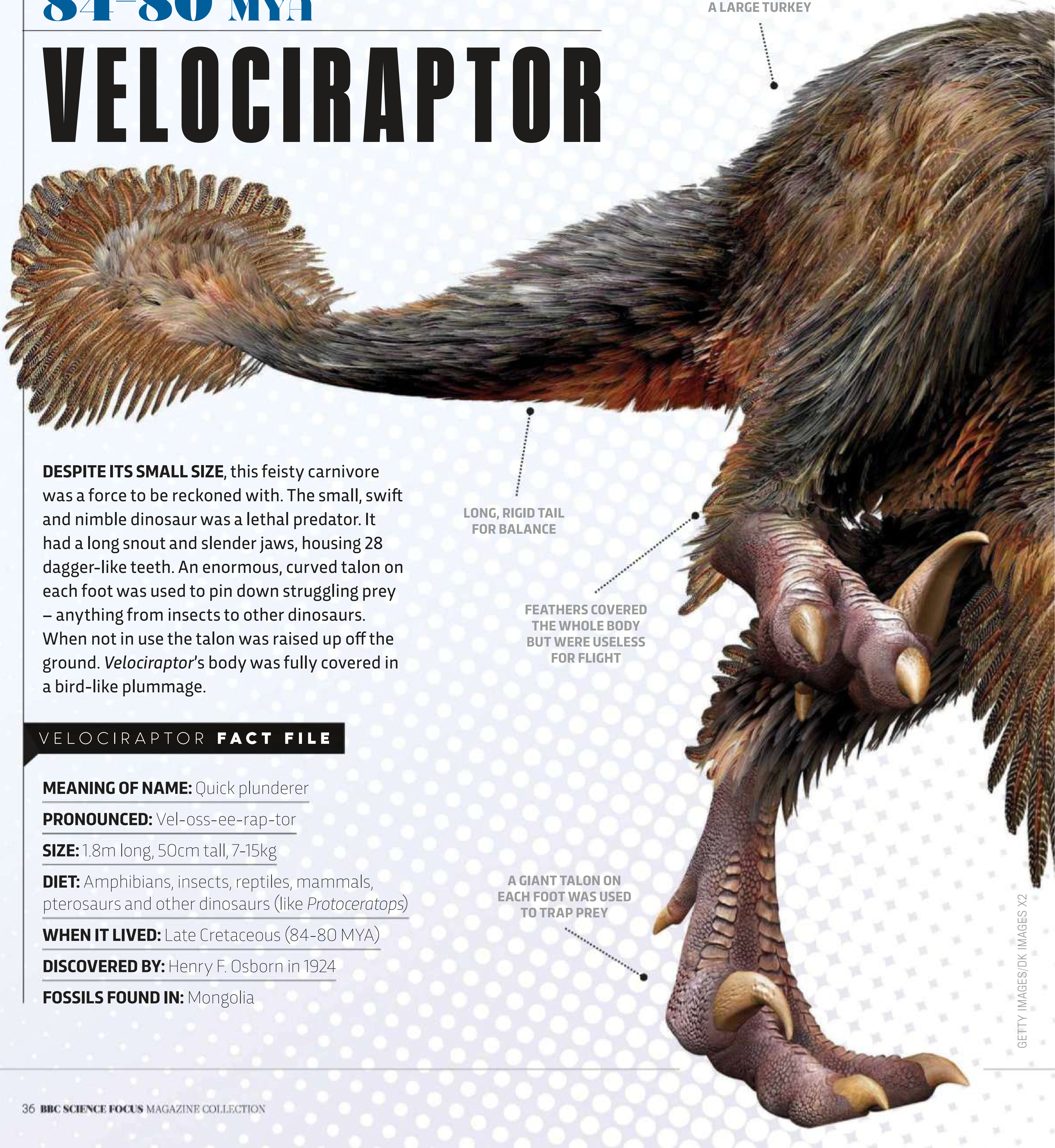
ARGENTINOSAURUS HAD AN ESTIMATED POO VOLUME OF 15 LITRES – ALMOST THREE TIMES THE VOLUME INSIDE A FOOTBALL

Spinosaurus **(left) was the largest carnivorous dinosaur that ever lived – bigger than *T. rex***

GETTY IMAGES X4

84-80 MYA

VELOCIRAPTOR



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DESPITE ITS SMALL SIZE, this feisty carnivore was a force to be reckoned with. The small, swift and nimble dinosaur was a lethal predator. It had a long snout and slender jaws, housing 28 dagger-like teeth. An enormous, curved talon on each foot was used to pin down struggling prey – anything from insects to other dinosaurs. When not in use the talon was raised up off the ground. *Velociraptor*'s body was fully covered in a bird-like plummage.

VELOCIRAPTOR **FACT FILE**

MEANING OF NAME: Quick plunderer

PRONOUNCED: Vel-oss-ee-rap-tor

SIZE: 1.8m long, 50cm tall, 7-15kg

DIET: Amphibians, insects, reptiles, mammals, pterosaurs and other dinosaurs (like *Protoceratops*)

WHEN IT LIVED: Late Cretaceous (84-80 MYA)

DISCOVERED BY: Henry F. Osborn in 1924

FOSSILS FOUND IN: Mongolia

DID YOU KNOW

VELOCIRAPTOR WAS 12 TIMES SHORTER THAN *T. REX* BUT COULD RUN FASTER AT A MAXIMUM SPEED OF 40KM/H

76-74 MYA

EDMONTONIA

WAS A 4-METRE LONG herbivore with some serious armour – spikes and bony plates called 'osteoderms'. It had relatively poor vision, but a good sense of smell, thanks to an extensive and uniquely folded nasal passage.

68-66 MYA

TYRANNOSAURUS REX

SURELY THE MOST INFAMOUS DINOSAUR, the 'tyrant lizard' was one of the most ferocious predators of all time. With a bite three times stronger than a lion's, and around 60 saw-edged teeth each measuring up to 20cm long, *T. rex* could chomp through bone. It hunted some of the most heavily armoured dinosaurs. But it also scavenged for food – the part of the brain responsible for smell was fairly large, meaning it could sniff out carcasses.

GABRIEL UGUETO, GETTY IMAGES

DID YOU KNOW

T. REX COULD RUN AT UP TO 20KM/H – WAY SLOWER THAN A FLEEING CAR DRIVING AT TOP SPEED (*JURASSIC PARK* PRODUCERS TAKE NOTE)

T.REX **FACT FILE**

MEANING OF NAME: King of the tyrant lizards

PRONOUNCED: Tie-ran-oh-sore-us

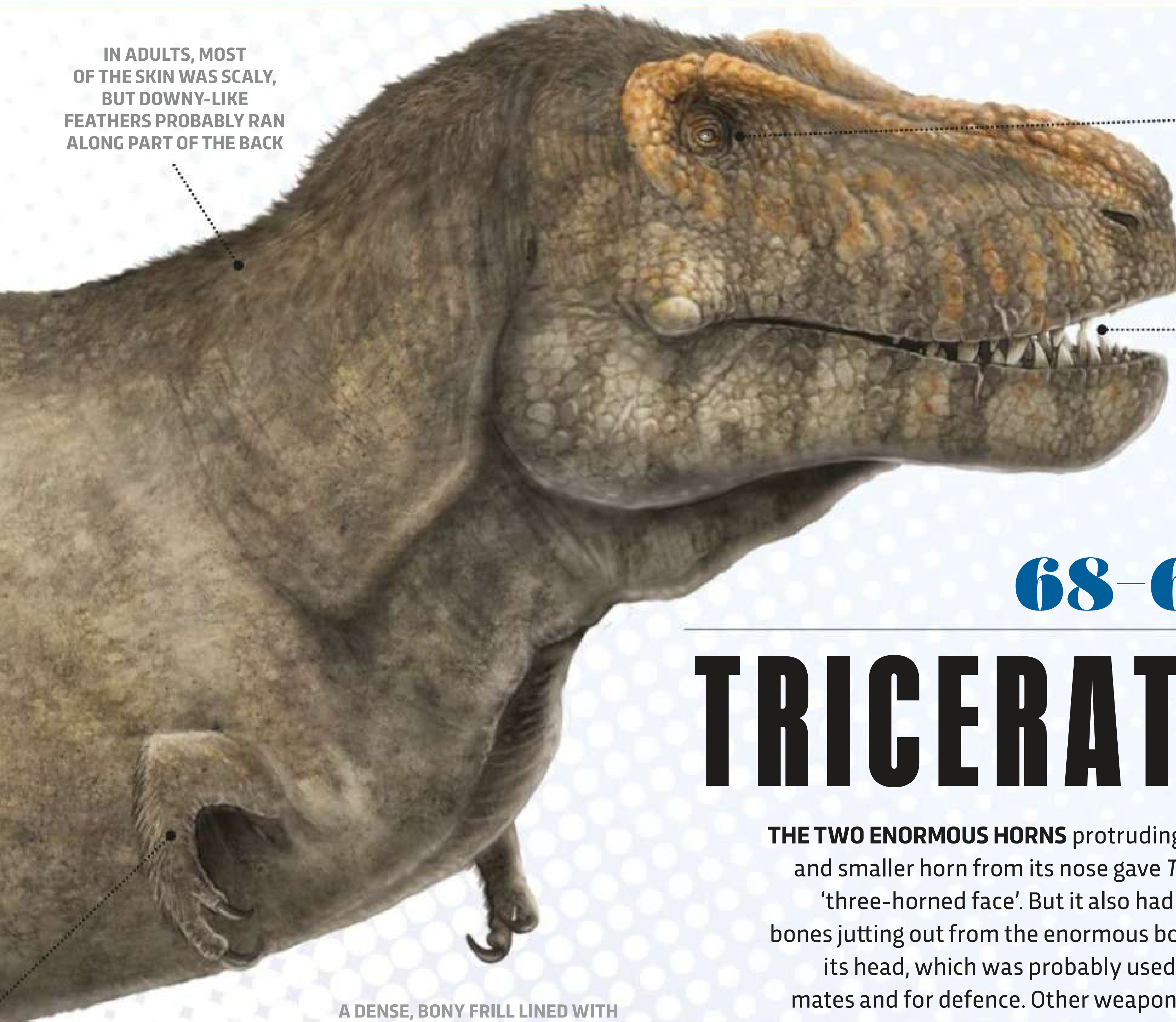
SIZE: 12m long, 3.5m to top of neck, 7,000kg

DIET: Large dinosaurs, such as *Triceratops* and *Edmontosaurus*

WHEN IT LIVED: Late Cretaceous (68-66 MYA)

DISCOVERED BY: Barnum Brown credited with discovery in 1902

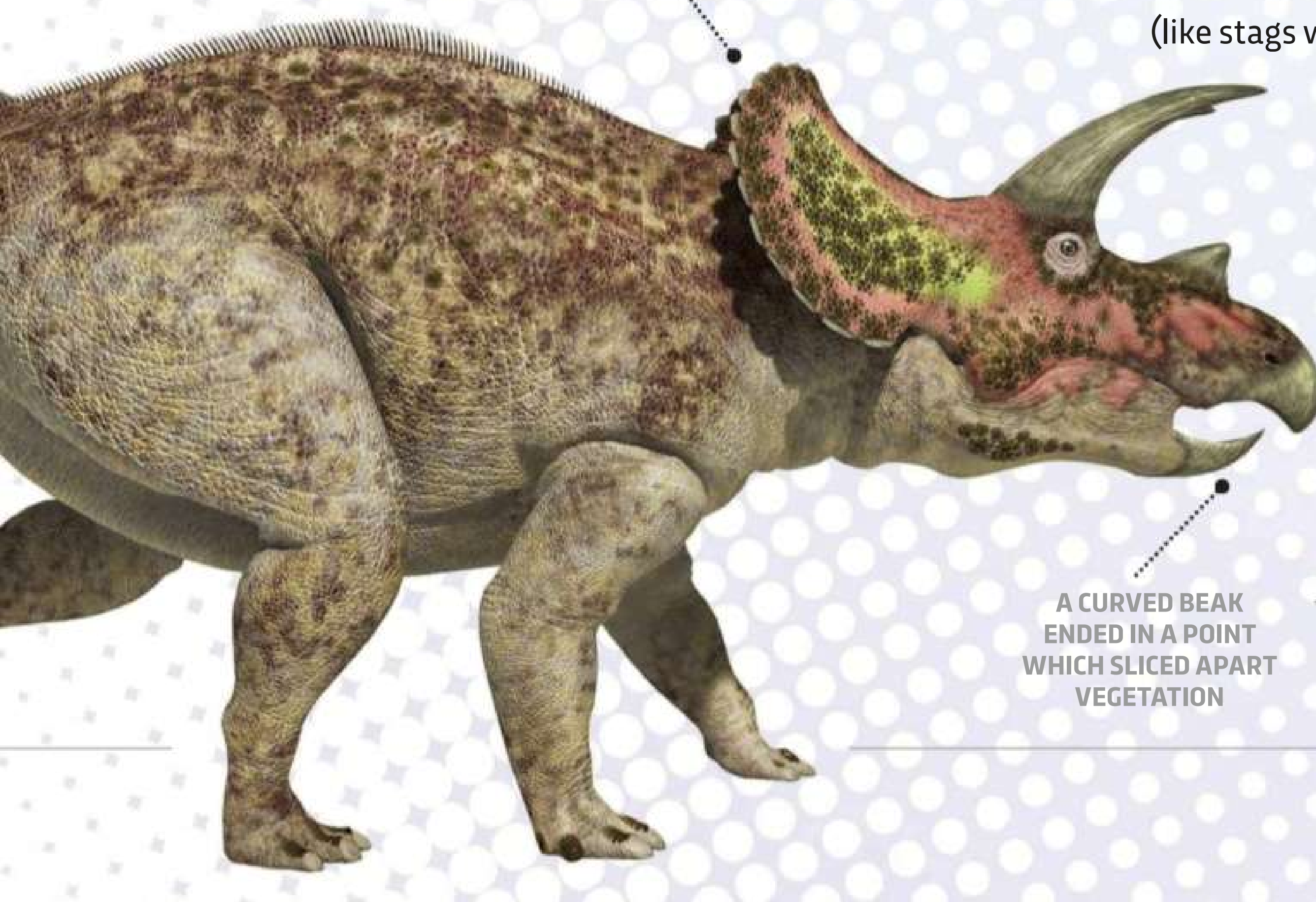
FOSSILS FOUND IN: USA and Canada



68-66 MYA

TRICERATOPS

THE TWO ENORMOUS HORNS protruding from above its eyes and smaller horn from its nose gave *Triceratops* its name – 'three-horned face'. But it also had a number of pointed bones jutting out from the enormous bony frill that crowned its head, which was probably used to impress potential mates and for defence. Other weapons, such as a powerful yet toothless beak and great batteries of interlocking, diamond-shaped teeth, were also used in battle for mates (like stags when they rut) or to defend against predators such as *T. rex*. Bite marks and broken horns show it sometimes fell prey to the beast.



TRICERATOPS **FACT FILE**

MEANING OF NAME: Three-horned face

PRONOUNCED: Tri-serra-tops

SIZE: 9m long, 3m tall, 5,500kg

DIET: Low-growing shrubs such as ferns

WHEN IT LIVED: Late Cretaceous (68-66 MYA)

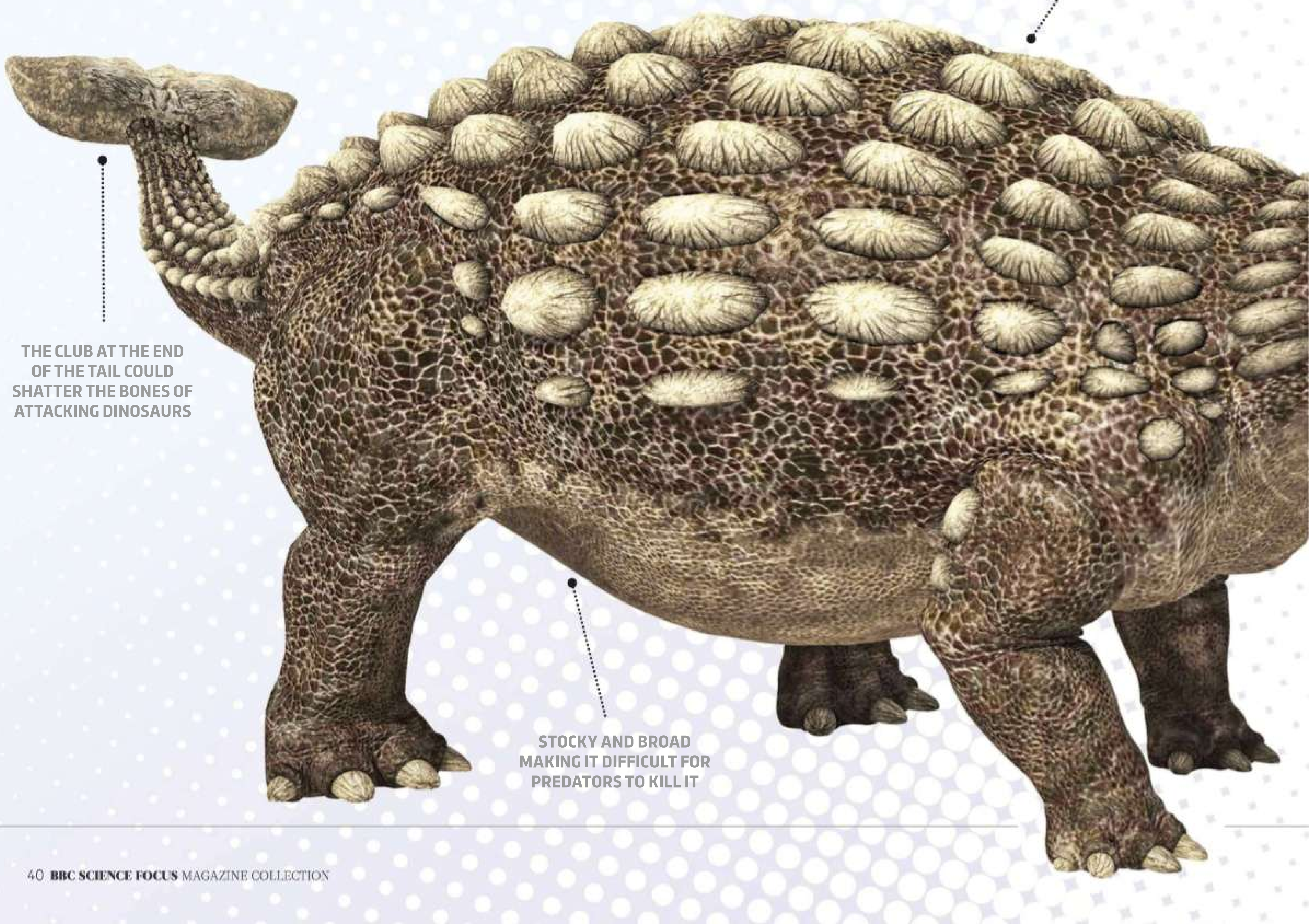
DISCOVERED BY: John Bell Hatcher in 1888

FOSSILS FOUND IN: USA

68-66 MYA

ANKYLOSAURUS

WITH ITS THICK LAYER of armour, *Ankylosaurus* was tougher than any army tank. Its outer layer of skin was reinforced with bony plates called 'osteoderms'. But most predators wouldn't even manage to reach its robust body because of the deadly swinging club at the end of its tail. With this arsenal of weaponry, you might expect *Ankylosaurus* to be a formidable predator, but it was actually a herbivore, using its artillery for defence. *Ankylosaurus* had numerous leaf-shaped teeth at the back of its jaws, but the front of the mouth was toothless and equipped with a horny beak to pluck plants from the undergrowth. It may have digested the plant matter via fermentation, the same process used to produce alcohol.



ANKYLOSAURUS **FACT FILE**

MEANING OF NAME: Stiff lizard

PRONOUNCED: An-kie-loh-sore-us

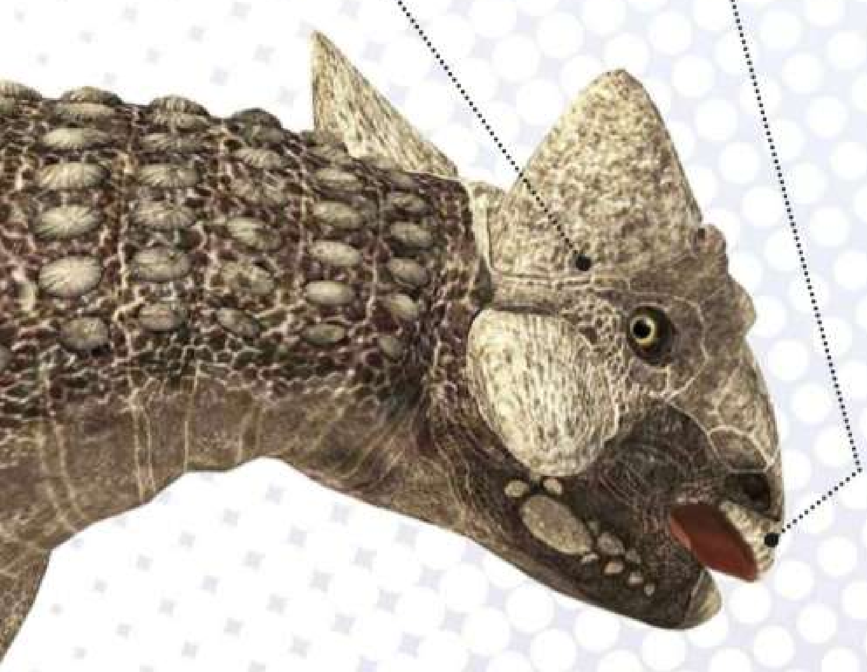
SIZE: 7m long, 1.7m tall, 7,000kg

DIET: Specific flora in the undergrowth

WHEN IT LIVED: Late Cretaceous (68-66 MYA)

DISCOVERED BY: Barnum Brown in 1906

FOSSILS FOUND IN: USA and Canada



DID YOU KNOW

70% OF ALL *ANKYLOSAURS* THAT HAVE BEEN DISCOVERED WERE FOSSILISED UPSIDE DOWN, BECAUSE THE FLOATING LIFELESS BODIES OVERTURNED BEFORE SINKING TO THE SEAFLOOR

GETTY IMAGES X2

66 MYA
CRETACEOUS-TERTIARY
Mass extinction event

Probably the most famous mass extinction event. An asteroid impact, likely followed by volcanism, killed off the dinosaurs and about 75 per cent of species. Since then, birds and mammals have evolved to become the dominant land species.

GETTY IMAGES

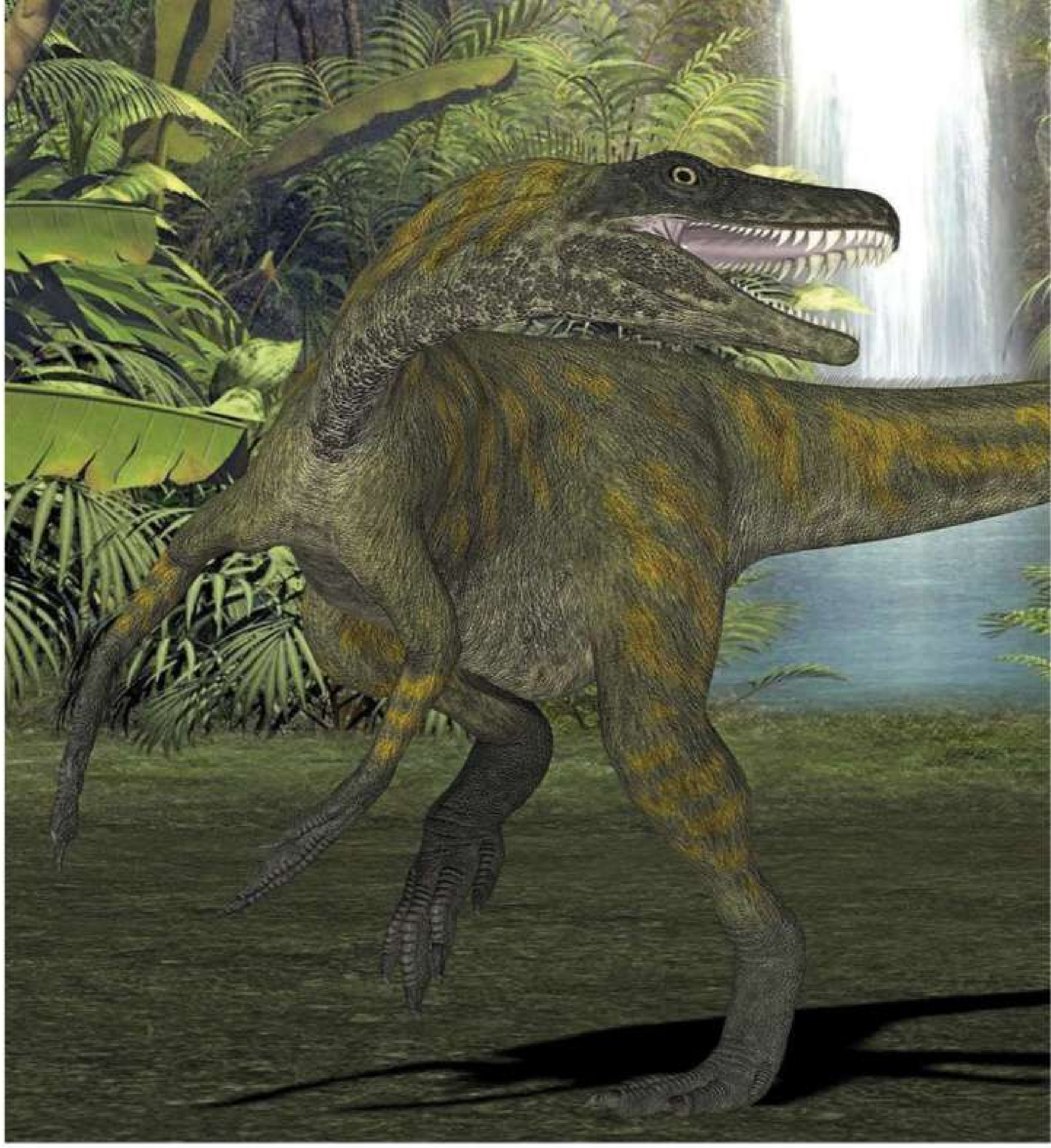
HOW DINOSAURS CONQUERED THE WORLD

Brute force was thought to have been responsible for the dinosaurs' rise to dominance, but evidence is building for a different explanation

WORDS: **DARREN NAISH**

The Mesozoic Era – the vast span of time that extended from 250 to 66 million years ago – is famously described as the 'Age of Dinosaurs'. It was once thought that these mighty reptiles came to rule the planet through sheer brute force, but a discovery made over 50 years ago of the earliest large dinosaur known, called *Herrerasaurus*, would turn this idea on its head. Subsequent fossil finds in recent years have added weight to the argument that the dinosaurs didn't out-muscle rivals to become the dominant force. Indeed, it now seems that their success was nothing more than a fluke.

Discovering how the dinosaur age got started has never been an easy task. Species from the Triassic period at the dawn of the Mesozoic have been known since the 1800s. But the creatures discovered, including the bipedal predator *Coelophysis* and the omnivorous, long-necked *Plateosaurus*, are mostly from the latest part of the Late Triassic – they



are about 210 million years old. These animals were fairly large, three or more metres long, with sophisticated skulls that show that they were relatively advanced members of the dinosaur family tree. The lack of older, more primitive, dinosaurs long made it difficult to understand what happened during the earliest stages of their evolution.

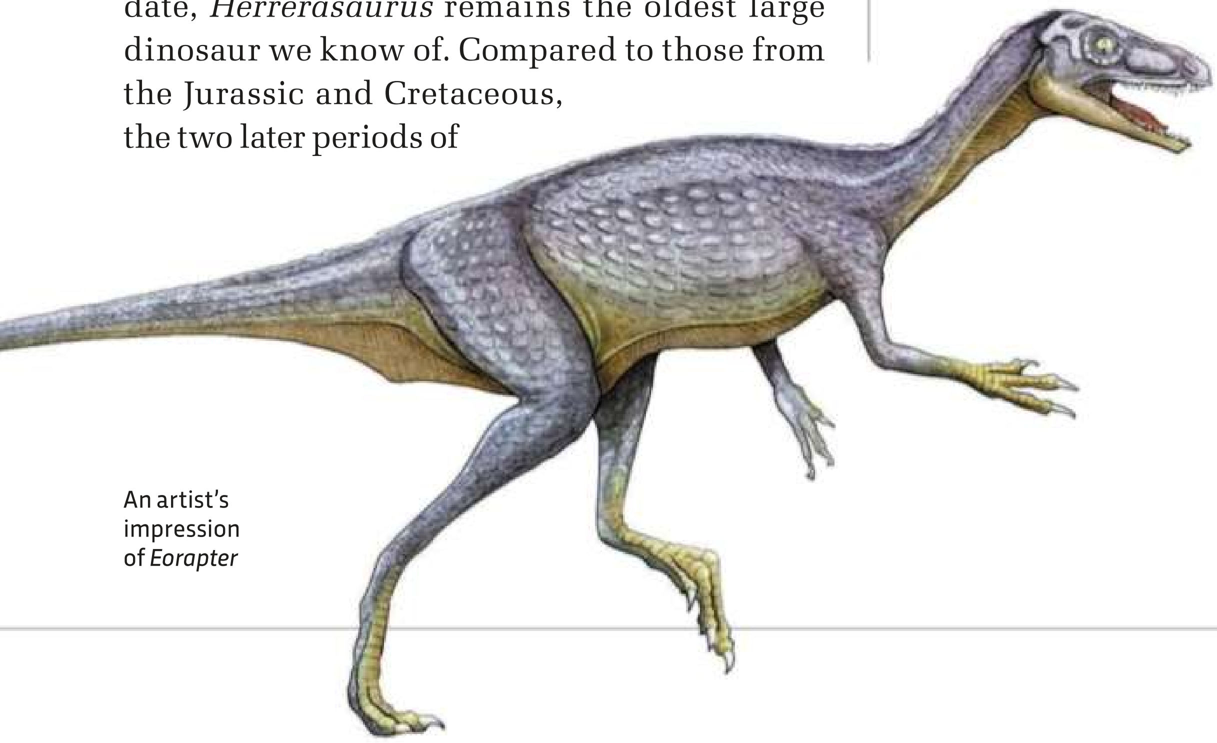
A FIND FROM FURTHER BACK

It was the discovery of *Herrerasaurus* in 1963 that gave us a window into some of the earliest years of the dinosaurs. A team led by Argentine palaeontologist Dr Osvaldo Reig studied the remains of a surprisingly old dinosaur at Ischigualasto in northwestern Argentina. Reig named the animal *Herrerasaurus* after local farmer Victorino Herrera, who first spotted the fossils in 1959. These remains are from the earliest part of the Late Triassic, and hence are about 230 million years old. Reig knew *Herrerasaurus* was a predator of some sort, but the remains were not good enough for him to reconstruct the animal's appearance and lifestyle confidently.

Far better specimens were discovered in 1988, when Dr Paul Sereno at the University of Chicago and colleagues searched anew at the same spot. Thanks to these finds, we now know *Herrerasaurus* was bipedal, with a narrow snout, long, 're-curved' teeth that swept back making it hard for prey to escape, and large raking claws on the inner three fingers of its five-fingered hands. It was a large dinosaur, capable of reaching 4.5m long – roughly the length of a large car – and weighing perhaps 200kg. To date, *Herrerasaurus* remains the oldest large dinosaur we know of. Compared to those from the Jurassic and Cretaceous, the two later periods of the Mesozoic Era, 4.5m is not large at all. But compared to other dinosaurs from the early part of the Late Triassic, *Herrerasaurus* was a giant.

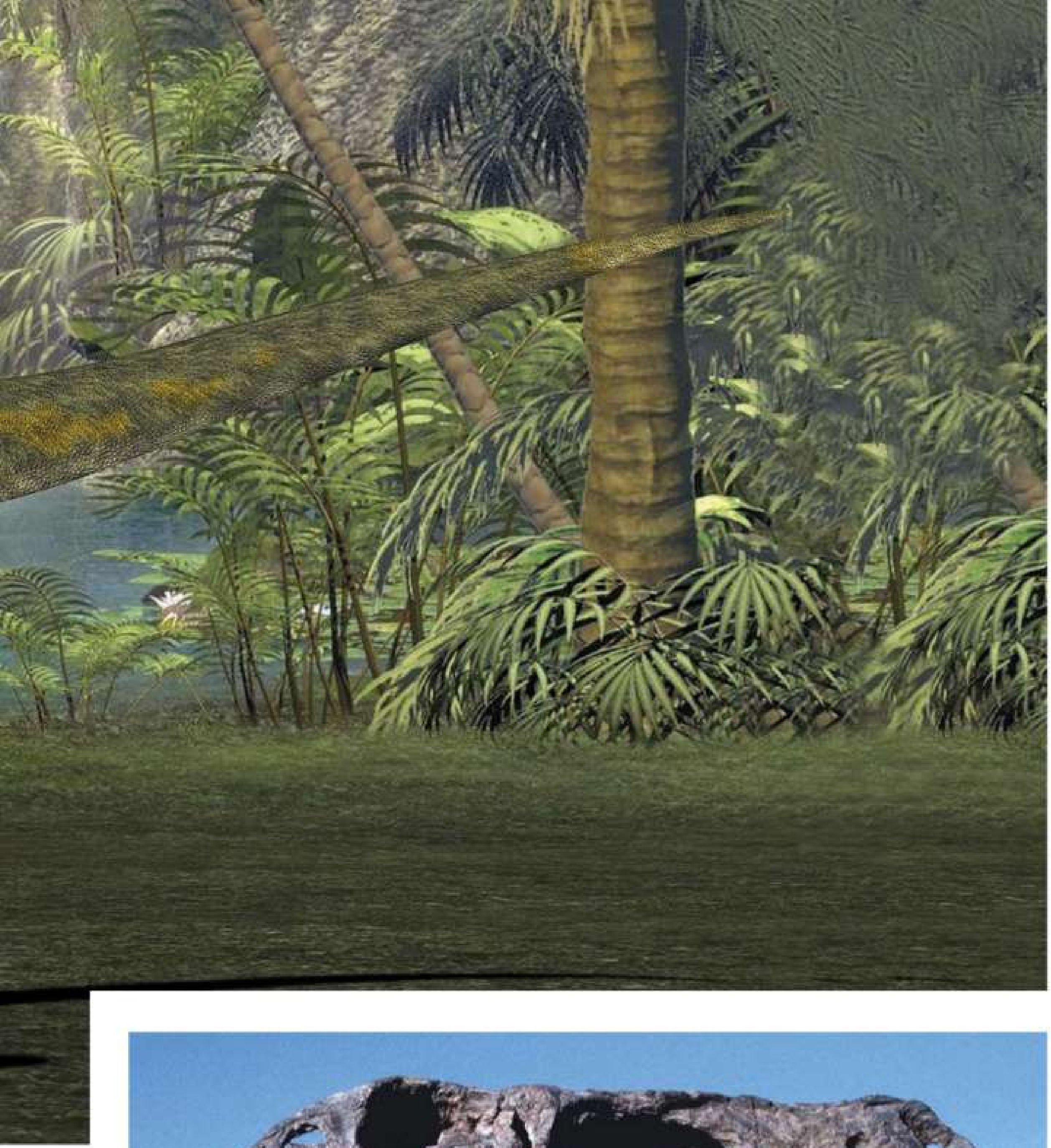
IT'S BECOME CLEAR THAT THE EARLIEST, TIMID DINOSAURS DID NOT GO THROUGH A RAPID EVOLUTION

In 1991, Sereno and colleagues discovered another Ischigualasto dinosaur, which was later dubbed *Eoraptor*. It seems to have been a far more typical Triassic dinosaur and, indeed, a variety of similar-aged species are now known. All are lightly built and less than two metres long. Most must have been omnivores, foraging in the undergrowth and generally keeping out of sight. The timid species discovered belong to different branches of the dinosaur family tree, so we can be sure that being small and



An artist's impression of *Eorapter*

ALAMY, GETTY IMAGES X2



TOP: *Herrerasaurus* was one of the earliest dinosaurs. It had a sliding lower jaw — useful for snaring prey

ABOVE: A skull of *Herrerasaurus* found in Patagonia

inconspicuous was the lifestyle adopted by most early dinosaurs.

These early dinosaurs were far from alone in the Triassic world. Dinosaurs are part of a major group of reptiles termed archosaurs. Early in the Triassic, archosaurs diverged into one lineage that led to dinosaurs and later to birds, and another that led to crocodiles and their kin. These are respectively termed 'bird-line' and 'croc-line' archosaurs.

Some of the croc-line archosaurs that lived in the Triassic were top predators. At more than five metres long, they were able to attack and defeat an animal like *Herrerasaurus*. In fact, many croc-line archosaurs evolved body shapes and lifestyles that mimicked those of the dinosaurs that would emerge more than 50 million years later.

Meanwhile, the ancestors of mammals – the synapsids – included small, furry, mammal-like forms as well as tusked, pig-sized herbivores and badger- and rat-sized omnivores and predators. For much of the 20th Century, it was believed that dinosaurs were competitively superior to croc-line archosaurs and synapsids. It was thought that members of these groups literally tussled for dominance on the Triassic plains, and with their long, erect legs, clawed hands and sprightly abilities, the dinosaurs were able to win the evolutionary arms race. Croc-line archosaurs would, so it was supposed, have had to abandon their claim on the land and eke out a living forever afterwards as marsh- and lake-dwelling crocodiles and alligators.

But new discoveries have painted a more complex picture. Claims that dinosaurs were special relative to other archosaurs and to synapsids no longer ring true. Indeed, the earliest, timid dinosaurs did not go through a rapid evolution that would turn them into fighting machines.

A SERIES OF UNFORTUNATE EVENTS

Since 2003, there has been a burst of discoveries of dinosauromorph fossils – dinosauromorphs being the creatures that gave rise to the dinosaurs and lived alongside them for millions of years in the Triassic. These new fossils have shown that dinosaurs were not especially different from the dinosauromorphs. So the dinosaurs emerged quietly, without any dramatic increase in body size or important shift in lifestyle or ecology from among this group of small predators or omnivores. Looked at objectively, there is nothing in the fossil record that makes the success of dinosaurs seem at all inevitable. In fact, it was a world that belonged to croc-line archosaurs. So, what happened? How did dinosaurs go from being small, furtive animals of the background to a dominant global force?

The strongest evidence appears to show that two mass extinction events – both occurring during the last part of the Triassic – removed

WHAT IF THE DINOSAURS' RIVALS HAD SURVIVED?

What might have happened if the extinction events that enabled the dinosaurs to rise to dominance never occurred?

For starters, it's likely the croc-line archosaurs would have persisted as top predators, preventing the appearance of amphibious crocodiles and alligators. Dinosaurs and other bird-line archosaurs would have continued to live in the background and remain small. The dominance of the croc-line archosaurs would have left few ecological niches for the dinosaurs to exploit, so many of the species we know to have existed would not have developed. Interestingly, this means that birds would not have appeared, since their origin was contingent on the diversification and success of predatory dinosaurs.

What about mammals? We can be confident that small burrowers, swimmers and climbers would have evolved during the Mesozoic, and would have tried to avoid the attentions of croc-line archosaurs. The evolution of large mammals – whales, antelopes and humans, for example – would have depended on the asteroid that ended the reign of the dinosaurs 66 million years ago killing off croc-line archosaurs.

If this extinction event at the end of the Cretaceous did kill off croc-line archosaurs, mammals would have to contend with any surviving small-bodied dinosaurs. Mammals and dinosaurs would have raced to evolve a large size. But, even if large dinosaurs had evolved, it's likely humans would still have risen to dominate, taming and farming them for our own ends.

Dinosaurs (top right) eventually came out on top, despite competition from croc-line archosaurs (top left) and early mammals (bottom right)

THE DOMINENCE OF DINOSAURS APPEARS TO BE BECAUSE MANY OF THEIR COMPETITORS JUST DISAPPEARED

large-bodied synapsids and croc-line archosaurs from the equation, leaving dinosaurs to rule the world.

The first of these extinctions happened about 220 million years ago. Many larger-bodied synapsids died off at this time, as did various non-dinosaurian reptile groups and marine species. A climatic change, perhaps triggered by the splitting of the Pangaean supercontinent – the huge landmass that incorporated all the continents we know today – caused aridity in many areas. It has been suggested that the resultant change in vegetation and rainfall initiated a cascade of ecological consequences.

The second mass extinction event happened at the end of the Triassic, 200 million years ago. It seems to have caused major, rapid changes to the global flora and fauna. An asteroid impact is the likely cause, just as it is for the extinction event of 66 million years ago that wiped out the dinosaurs (except for the birds, the lineage of dinosaurs that survived).

There is even a potential 'smoking gun' for this Triassic strike: the enormous Manicouagan Crater in Quebec. Representing the impact site of an object perhaps 5km across, it is presumably big enough to have caused major perturbations in the global ecosystem. Similar-aged craters in western Canada, France, the Ukraine and North Dakota have been suggested as evidence for a series of impact events.

The Manicouagan Crater means it might have been formed as many as 214 million years ago. But several pieces of evidence in recent years, including a burst in fern growth, have provided support for another impact happening 200 million years ago. It's known that when other plant species are wiped out,

TOP: The Manicouagan Crater in Quebec is thought to have been caused by a 5km-wide asteroid at the end of the Late Triassic

ABOVE LEFT: The remains of a *Redondasaurus* slowly decompose on a dried riverbed – an imagined scene following the Triassic-Jurassic extinction

ferns enjoy a huge growth in population. Less controversial is the massive volcanism that occurred at the same time in the northern part of the supercontinent Pangaea. It appears to have caused global warming and ecosystem collapse.

RULING THE ROOST

After these events, dinosaurs flourished – the fact that they made 50 per cent of the tracks we now see from this time is evidence for this. Furthermore, the size of the track-makers doubles during the same period. As big animals that were living out in the open and sitting at the top of their respective food pyramids, croc-line archosaurs were presumably more adversely affected by the extinction events than the mostly small, ecologically generalised dinosaurs. The general pattern of the fossil record shows croc-line archosaurs doing okay prior to the event, but are all but absent after it.

The dominance of dinosaurs, then, appears to owe itself to the fact that many of their competitors simply disappeared. Had those extinctions not occurred, the Mesozoic could have been the age of the crocodile rather than the dinosaur. Half a century on from the discovery of *Herrerasaurus*, we know that the dinosaurs weren't as formidable a force as was once thought – they were fortunate survivors. SF

BBC RADIO 4

*Listen to an episode of **Frontiers** discussing dinosaur discovery*
bbc.in/2N5asEo

by **DR DARREN NAISH** *(@TetZoo)*
*Darren is a palaeontologist at the University of Southampton and author of **Dinosaurs: How They Lived. and Evolved.***

SCIENCE PHOTO LIBRARY

HOW WE KNOW WHAT DINOSAURS LOOKED LIKE

Today we take the appearance of dinosaurs for granted. But it's taken centuries of careful study to learn how to accurately read the clues in the fossil record

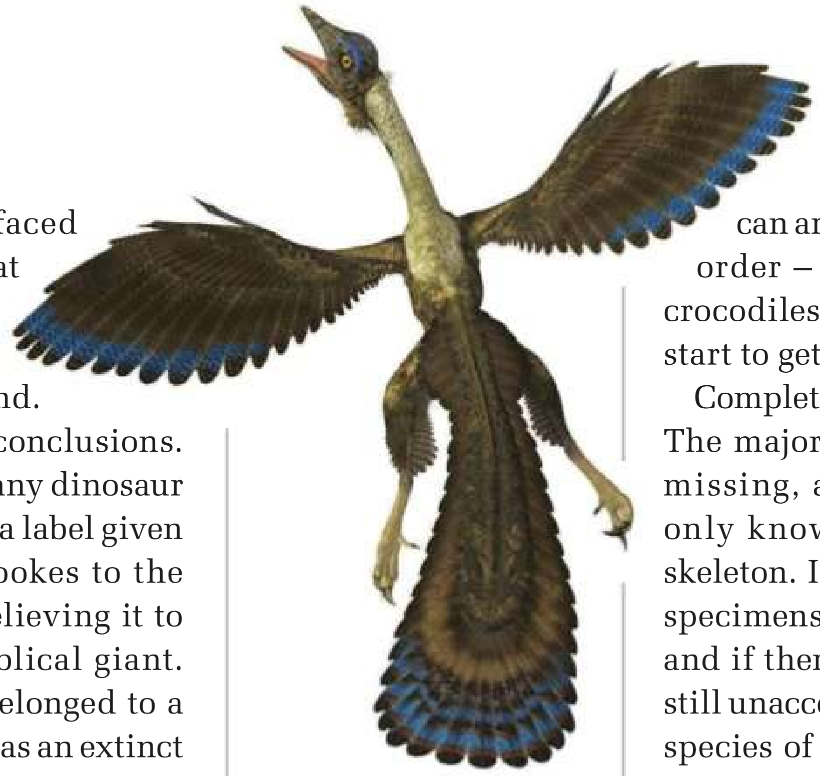
WORDS: JOHN PICKRELL

Back in October 2015, a new dinosaur was revealed from the 66-million-year-old Hell Creek formation in South Dakota, in the US. Colourful pictures of this bipedal, feathered predator were published around the world. Experts behind the discovery of *Dakotaraptor* reported that it had large, sickle-shaped claws on the second toes of its hind feet and would have been slightly taller than a human. This made it one of the largest dromaeosaurs (swift seizers), the group to which *Velociraptor* also belongs.

We take these kinds of reconstructions for granted these days, but just how realistic are they, and how do we know what dinosaurs really looked like?

Our first attempts to imagine the animals that left fossils behind were in prehistory. Dragons appeared in Chinese texts as far back as 1100 BC and may have been influenced by dinosaur bones. Similarly, griffins (part eagle, part lion) are known from Ancient Greek myths; the inspiration may have come from fossils of the beaked dinosaur *Protoceratops*.

Sinosauropteryx lived around 126 million years ago in what is now northeastern China



When ancient people were faced with strange bones, they did what we do today and used the best knowledge available to reconstruct the creatures that left them behind. Sometimes this resulted in poor conclusions. The first name assigned in print to any dinosaur remains was *Scrotum humanum* – a label given by British physician Richard Brookes to the broken end of a femur in 1763, believing it to be the fossilised testicles of a Biblical giant. We now know that the leg bone belonged to a *Megalosaurus* – correctly described as an extinct reptile by William Buckland in 1824. You can't entirely blame Brookes for his conclusions, as dinosaurs would not be described as a group until 1842. That was when Richard Owen, head of what is now the Natural History Museum, revealed a new class of strange, extinct creatures he called dinosaurs.

He imagined *Iguanodon*, *Megalosaurus* and *Hylaeosaurus* to be reptiles with legs sprawled out to the sides and scaly grey or green skin, like modern lizards or crocodiles. Since then, we have completely revised our ideas of the appearance of dinosaurs, and much of this began with the description of another American dromaeosaur called *Deinonychus* in the 1960s. John Ostrom at Yale University made the revolutionary suggestion that this species was a bird-like, fast, warm-blooded pack hunter, and championed the idea that birds were dinosaurs. He was vindicated when *Sinosauropteryx*, the first known feathered dinosaur, was found in China in 1996.

BONES ARE ONLY THE START OF A DINOSAUR RECONSTRUCTION

FILLING IN THE GAPS

When faced with new fossils today, palaeontologists have a much bigger body of knowledge to draw upon when creating reconstructions. Our knowledge has increased to the degree that we can even tell the colours of the feathers of a range of dinosaur species.

All dinosaur reconstructions begin with their fossilised bones. If palaeontologists are lucky enough to have found a complete skeleton, they can arrange these bones into the appropriate order – based on how the bones of birds, crocodiles and even people are arranged – and start to get a sense of the shape of the creature.

Complete dinosaur skeletons are rare though. The majority of fossil specimens have bones missing, and a great number of species are only known from a fraction of the original skeleton. In these cases, the bones of different specimens can be compared to fill in the gaps and if there are parts of the skeletons that are still unaccounted for, experts will look to related species of dinosaur for help.

Detailed knowledge of the anatomy of many modern species (a field known as comparative anatomy) is helpful here and many dinosaur experts are excellent anatomists. To those in the know, small details in the shape of bones can reveal a lot about the animal they came from. For example, dinosaurs and birds (which are a kind of theropod dinosaur) have a hole in their pelvis called a perforated acetabulum into which the top of the thigh bone (femur) fits. This is a unique trait of dinosaurs, allowing them to stand erect with their legs beneath their bodies, rather than out to the sides as in other reptiles. The dinosaur hip also allows experts to identify the two major branches of the dinosaur family: ornithischians and saurischians.

Theropods, the carnivorous group of saurischian dinosaurs to which *T. rex*, *Allosaurus* and *Dakotaraptor* belong, have a series of other telltale traits in the fossils. These include hollow bones full of air pockets, three fingers on the hands, and much reduced fourth and fifth digits on the feet. Maniraptorans, the group of theropods from which birds evolved, have more distinct features, including an unusual wrist joint with a bone called a semilunate carpal. This gave these carnivores more flexible wrists for seizing prey with their hands and allowed the flight stroke of birds to evolve.

Bones are only the start of a dinosaur reconstruction, though. It's also important to think about muscles. For example, discs of muscle between the vertebrae of a sauropod dinosaur

GETTY IMAGES, H RAAB/WIKIPEDIA

what is this?

ARCHAEOPTERYX

The world-famous fossil of *Archaeopteryx*, 'the first bird', housed at the Museum für Naturkunde in Berlin. Hermann von Meyer reported finding this almost-complete skeleton, along with a fossilised feather in 1861, in limestone near Solnhofen, southern Germany. An artist's impression of the animal is on the opposite page.

such as *Brachiosaurus* or *Diplodocus* would have made a great difference to the length of the animal. Muscles are added by referencing the positions and shapes of muscles in living animals. Fossilised bones often have 'muscle scars' that show attachment points, which aid in this process. Since we know that larger, modern animals have bigger marks, we know we need to add bigger muscles to those dinosaurs.

Our understanding of the finer details of dinosaur anatomy has also improved thanks to 3D computer models that use the physiology of living animals to make predictions about extinct species. Palaeontologists are increasingly making use of digital, biomechanical models to test their ideas about how dinosaurs walked and used their jaws.

Finally, layers of fat and skin are added to reconstructions, as well as scales, feathers, armour, crests and other features such as cheeks, lips, claws and beaks. There are surprising pieces of evidence that come to bear on these decisions too. We have some truly incredible skin impressions for a range of dinosaurs – particularly herbivores like *Edmontosaurus* and *Saurolophus*. The prevalence of scaly skin impressions in the fossils of herbivorous dinosaurs has led experts to believe that most had scales instead of feathers (but a handful of herbivorous dinosaurs have been found with bristles and other feather-related features).

We also know that some herbivores, particularly the armoured ankylosaurs, were covered in bony plates, spikes and knobs. These bony growths in the skin, known as osteoderms, often fossilised and give a good sense of how animals like *Scelidosaurus* would have appeared.

In herbivorous dinosaurs there are other features that we can infer from the bones in the skull. Duck-billed hadrosaurs have large grinding teeth at the backs of their jaws and it's likely that these were covered with cheeks, allowing them to hold more food in their mouths for chewing before swallowing. In other dinosaurs, such as *Protoceratops*, *Triceratops* and *Oviraptor*, we can see the inner bony part of a beak that, in life, would likely have been covered with an outer keratinous layer as in birds today. Keratin is the same tough protein that feathers, hair, fur and fingernails are made of. Did dinosaurs have lips? This is something we still don't know, and is an area of current debate.

FLUFFY THEROPODS

In contrast to the herbivores, many carnivorous theropods were probably covered in feathers. Well-preserved fossils of nearly 50 species – mostly from China's northeastern province of Liaoning – show a range of feathery coverings, from downy, insulating 'dino-fuzz' to flashy display and flight feathers. Some of these animals are so exquisitely preserved that we can see the shape and arrangement of feathers right across their bodies.

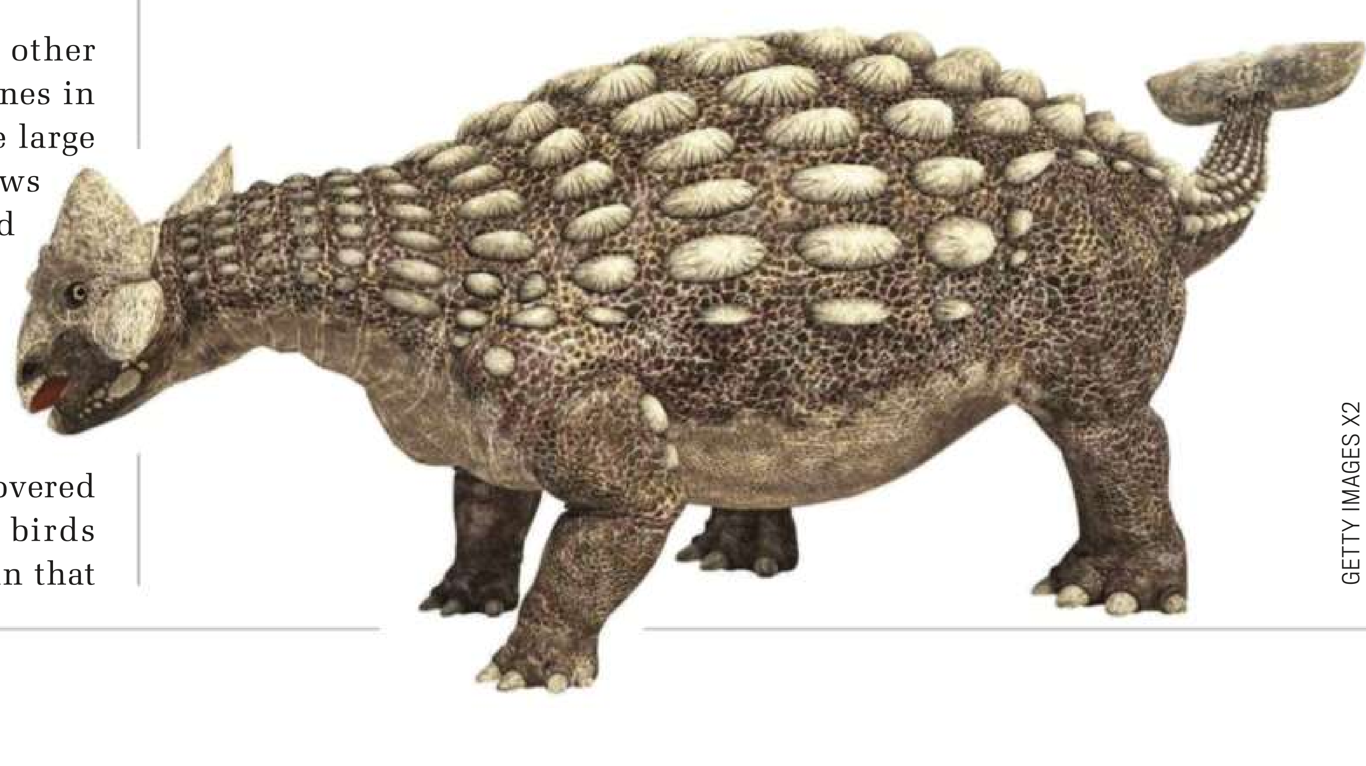
Though most of these feathered dinosaurs have been found in China, the spread of species across the family tree suggests that many theropods in other parts of the world were feathered too. We just have a fantastic window into the past with Liaoning because of the type of preservation found in its volcanic deposits.

Sometimes we have other evidence of feathers, such as marks on the forearm bones of *Velociraptor*, which correlate to the 'quill knobs' where the ligaments of flight feathers attach on pigeons today. It's this feature in *Velociraptor* fossils from Mongolia that led experts to assume all dromaeosaurs had small 'wings' on their forearms – a feature now confirmed by the Chinese fossil of another new dromaeosaur called *Zhenyuanlong*. Quill knobs were also found in the *Dakotaraptor* fossil.

But, in the years following the discovery of *Sinosauropteryx* in 1996, it became clear that most carnivorous theropods wouldn't have

ABOVE: Fossils of *Epidexipteryx* show that it may have used its feathers as a display to attract mates

BELOW: *Ankylosaurus* was covered in bony plates, spikes and knobs, known as osteoderms



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AFTER FEATHERS FIRST FOUND A USE IN INSULATION, THEY DEVELOPED ANOTHER PURPOSE

been able to fly – they didn't have fully formed wings or they weren't the right kind of shape. Palaeontologists began to realise that feathers evolved for another purpose and were only later co-opted for flight.

The feathers of many of these animals were simpler in structure than anything we'd recognise as feathers today and it's likely they were used like the downy fuzz of chicks for insulation. "To start with, feather structures are not all that complicated – they are a coat of simple filaments," says Dr Paul Barrett, a palaeontologist at the Natural History Museum in London. "These animals are small and quite active, they have elevated metabolic rates… and this is a way of retaining heat."

After feathers first found a use in insulation, they developed another purpose. In 2007, in Inner Mongolia, Chinese Academy of Science experts unearthed the fossil of a bird-of-paradise-sized dinosaur, which they called *Epidexipteryx*, Greek for 'display feather'. These scientists noted in a 2008 *Nature* article: "Ornamental plumage is used to send signals essential to a wide range of avian behaviour patterns, particularly relating

jargon buster

COMPARATIVE ANATOMY
The study of similarities and differences in the physical features of various species. This allows experts to make informed guesses about the appearance of extinct species based on living animals.

PALAEONTOLOGY
The study of prehistoric life, based on the fossils of animals, plants and other organisms, as well as the ages and details of the layers of rock they were found in.

THEROPOD
This large group of bipedal and mostly carnivorous dinosaurs includes *T. rex*, *Allosaurus* and *Sinosauropteryx*. The first birds evolved from theropods around 150 million years ago.

to courtship. It is highly probable that the [tail feathers] of *Epidexipteryx* had display as their primary function."

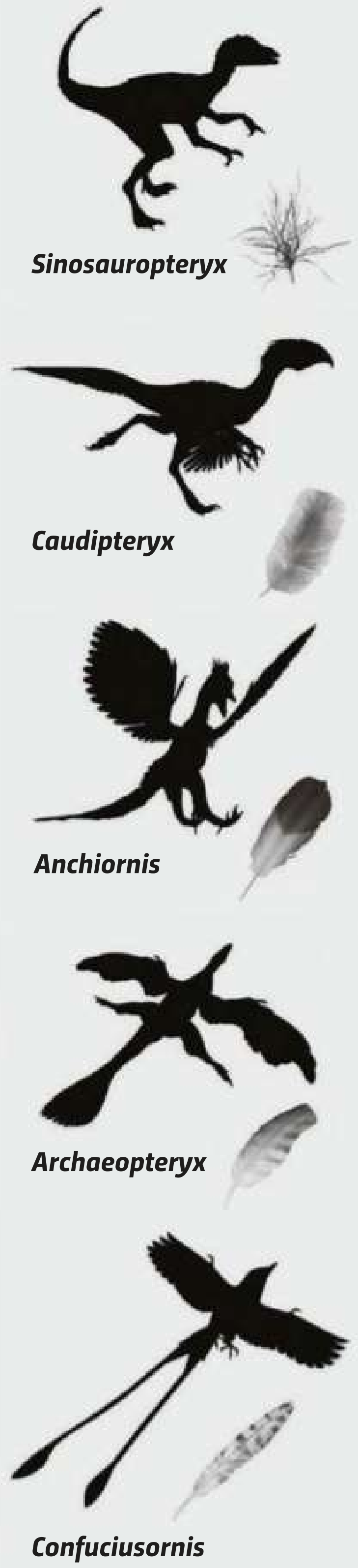
The fossilised creature retained traces of four, long, ribbon-like feathers, which it could have flicked and wafted as it danced to woo mates, as birds of paradise do today. This weird dinosaur was a compelling piece of evidence that early feathers were used for display too.

Other groups of dinosaurs had big 'pennaceous' feathers (with a central vane and interlocking barbs running off to either side) on their forearms and tails, which were more obviously used for showing off.

A 2013 study by experts including Phil Currie and Scott Persons at the University of Alberta, and Mark Norell at the American Museum of Natural History, provides perhaps the best evidence yet that dinosaurs used feathers for elaborate displays. Oviraptorids are parrot-beaked omnivorous theropods that had a 'pygostyle' tail, where the final few vertebrae are fused to form a ridged, blade-like structure. The researchers found marks on the bones of five different species of oviraptorids which suggested large muscles that would have allowed the stumpy tail to be flexed and posed in a number of ways. The conclusion was that male oviraptorids likely indulged in tail-shaking mating displays, much as turkeys and peacocks do today.

So there's good evidence of early feathers being used for insulation and display, but how did they come to find a flight function? Eventually, the extra surface area of feathers on the tail and forearms used for display would have offered some lift when jumping or gliding. Then evolution would have started to select for the running or flying functions of feathers, eventually leading to four-winged dinosaurs such as *Changyuraptor* and *Microraptor* that lived in the trees.

KNOWN TYPES OF DINOSAUR FEATHER

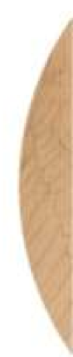


A LONGER LEGACY FOR PLUMAGE

Despite the fact that palaeontologists think many carnivorous theropods were covered in feathers, until recently, the consensus was that *T. rex* and other large theropods probably only had feathers as juveniles, if at all. The idea was that huge animals don't need insulation, as they lose heat slowly. But the discovery of a series of feathered relatives of Tyrannosaurus has turned this idea on its head. The first, *Dilong paradoxus*, was discovered by legendary dinosaur hunter Professor Xing Xu in Liaoning in 2004. As this lightly built, 125 million-year-old predator was relatively small, at two metres in length, its downy covering was not wholly unexpected.

More surprising, though, was nine-metre-high *Yutyrannus huali* discovered in 2012. Also from the Early Cretaceous deposits of Liaoning, this shaggy predator was closer in size to *T. rex*. It showed that downy feathers were probably more widespread among dinosaurs than anyone had expected. *Yutyrannus* is the largest feathered animal ever known to have lived.

A few of the new fossils, however, hint that feathers might have originated much deeper in the dinosaur family tree, and not so close to the ancestors of modern birds. For example, *Tianyulong confuciusi* was a small bipedal herbivore with a covering of fluff. Nothing unusual in that, except it's in the ornithischian group of herbivorous dinosaurs, which are very distant cousins to the carnivorous theropods. Another ornithischian – *Psittacosaurus*, a small



JASON BROUGHAM, ZANG HAILONG, MICK ELLISON

EVEN THE FILAMENTS OF PTEROSAURS ARE LIKELY TO BE A KIND OF PRIMITIVE FEATHER

Microraptor **is thought to have had feathers like this**

and early relative of *Triceratops* – also had bristle-like structures, which may have been a form of feather. And the Siberian species, *Kulindadromeus zabaikalicus*, is the best evidence so far that feathers may have been widespread across all dinosaur groups. This 1.5m-long ornithischian herbivore may have had three different types of feathery filament on its body and scales on its limbs.

There's even the tantalising possibility that feathers originated in the ancestors of animals that gave rise to dinosaurs and their sister group of flying reptiles, the pterosaurs. "Even the filaments of pterosaurs are likely to be a kind of primitive feather," argues Xu, a world expert on feathered dinosaurs at the Institute for Vertebrate Palaeontology in Beijing. Experts have known for some years that many pterosaurs had a fur-like covering, which perhaps helped them maintain a high metabolic rate for flight, but it's not yet clear if this is related to feathers or evolved independently.

Others aren't so sure that feathers were common across all dinosaur groups. There's no evidence of feathers in most other ornithischians, according to a 2013 study by David Evans of the Royal Ontario Museum and Dr Paul Barrett.

ABOVE: *Psittacosaurus* had bristle-like structures, which may have been a form of feather

BELOW LEFT: *Yutyrannus huali* had downy feathers over much of its body

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"We have lots of skin impressions from duck-billed and horned dinosaurs, and none of them show anything that looks like feathers," says Barrett. This could be because the ancestors of these dinosaurs started off with feathers and lost them, or that dinosaurs have within their genes the mechanism to easily evolve skin-related structures, he says. "They also have lots of armour and spikes that form in the skin too." It could explain why some groups have feathers, frills or armour and others don't.

The question now is did all dinosaurs and pterosaurs inherit feathers from the same common ancestor, or is it just that the group had a remarkable plasticity to play with different structures like bristles, quills, fuzz, fluff and, eventually, feathers sculpted for flight? Research is continuing, so hopefully we'll soon know more.

PREHISTORIC PALETTE

In the meantime, artists play an essential role in bringing dinosaurs to life, and often have expert anatomical and palaeontological knowledge to build on the scientific evidence with informed guesswork. Without these palaeoillustrators, the appearance of these animals would live only inside the minds of the scientists who discovered them.

In the last five years or so, the colours of dinosaur feathers have come into focus, but we may soon have a good idea of dinosaur skin colours too. We already know from the patterns of scales on some 'mummified' fossils that *Edmontosaurus* was probably adorned with stripy patterns and a number of studies have started to use electron microscopes to look at the structural patterns of tiny packages of pigment in the skin. In 2015, an international team of scientists used this technique to show that a prehistoric marine reptile called a mosasaur had a dark back and a pale-coloured belly.

Reconstructing animals from fossils is partly guesswork, but it's informed guesswork, building on the knowledge we've accumulated over the centuries. Today, we have a better idea of the appearance of dinosaurs than ever before. **SF**

by JOHN PICKRELL *(@john_pickrell)*
*John is a Sydney-based writer and the author of **Flying Dinosaurs** and **Weird Dinosaurs.***

Microraptor was a dinosaur, but very closely related to the first birds

JASON BROUGHAM

WHEN FLIGHT BEGAN

New discoveries have revealed fascinating insights into how dinosaurs became birds

WORDS: **JOHN PICKRELL**

Having finished a meal of fish, plucked from the surface of a nearby lake, the small creature begins to preen its blue-black, iridescent feathers. It looks like a modern crow, but a closer inspection reveals it has large flight feathers on its arms as well as its legs, a long tail that ends with a fan of feathers, claws emerging from its wings and a jaw full of tiny teeth in place of a beak.

We are high in the canopy of a Chinese forest 125 million years ago during the early Cretaceous, and this bird-like animal is in fact a small four-winged dinosaur called *Microraptor* – a member of the so-called dromaeosaur group of carnivores that also includes *Velociraptor* of *Jurassic Park* fame.

Microraptor was likely capable of flapping flight as well as gliding, and is in a wider group of feathered dinosaurs very closely related to the first birds. This and other dinosaurs discovered in recent decades, reveal that in the late Jurassic and early Cretaceous,

Archaeopteryx had both dinosaur and bird features

there were a number of experiments in flight that took place in the group of dinosaurs from which birds evolved.

Our knowledge about the transition from dinosaurs and birds has exploded in the past two and half decades, much of that down to a total of more than 160 new species of dinosaur that have been described in China over that time.

"The dinosaur-bird transition is now one of the best understood major transitions in the entire history of life," says Dr Steve Brusatte, a palaeontologist at the University of Edinburgh and author of *The Rise and Fall of the Dinosaurs*. "It has become a textbook example of what happens when a type of animal with a body design and lifestyle suited to one environment changes into something with a very different body, which allows it to prosper in another type of environment."

ROCK RECORD

By the early 1990s, most scientists had accepted that birds were not simply the descendants of dinosaurs, but that they were actually small, feathered, flying dinosaurs. But few experts could have predicted we would ever find dinosaur fossils with feather impressions – or that an avalanche of them was about to pour out of China.

"YOU CAN STITCH THESE FOSSILS TOGETHER ONTO THE FAMILY TREE AND SEE A DINOSAUR CHANGE INTO A BIRD"

An early clue to the links between dinosaurs and birds was the discovery of a fossil of the 'first bird' *Archaeopteryx*, in Germany in 1861. A series of fossils of *Archaeopteryx* – which lived 147 million years ago in the late Jurassic – show it was a bird that had wings with large flight feathers, but it also had a long bony tail and a jaw with teeth, more like its dinosaur ancestors. This similarity between *Archaeopteryx* and small dinosaurs found in the same Bavarian fossil deposits was remarked upon at the time.

But it wasn't until 1996 that a fossil emerged from the Chinese province of Liaoning that

left no doubt that birds had evolved from carnivorous ‘theropods’ similar to *Velociraptor*. The first of the feathered dinosaur fossils to be discovered, *Sinosauropteryx*, left palaeontologists dumbfounded with its obvious covering of fluffy plumage recorded in the rocks.

Experts have now found more than 50 feathered dinosaurs, most from China, but some from Mongolia, Germany, Canada, Russia, Myanmar and even Madagascar. Together, these fossils show us that the majority of carnivorous theropod dinosaurs had feathers, it’s just that only exceptional kinds of fossil preservation record them, and China has numerous such sites.

We now have a striking evolutionary sequence of fossils from dinosaurs to birds. “You can stitch these fossils together onto the family tree and see a dinosaur change into a bird, almost like a flip book or a film,” explains Brusatte. “There are some missing scenes, but by and large we know the main storyline: most dinosaurs had feathers, and feathers started as simple strands used for insulation but incapable of flight.”

ABOVE LEFT: **A fossil of *Sinosauropteryx*, which was the first dinosaur fossil to be found that had feathers**

BELOW: **An artist’s impression of *Sinosauropteryx***

ABOVE CENTRE: **A fossil of winged dinosaur *Anchiornis*, which shows its feathers**

ABOVE RIGHT: **The parrot-beaked *Gigantoraptor***

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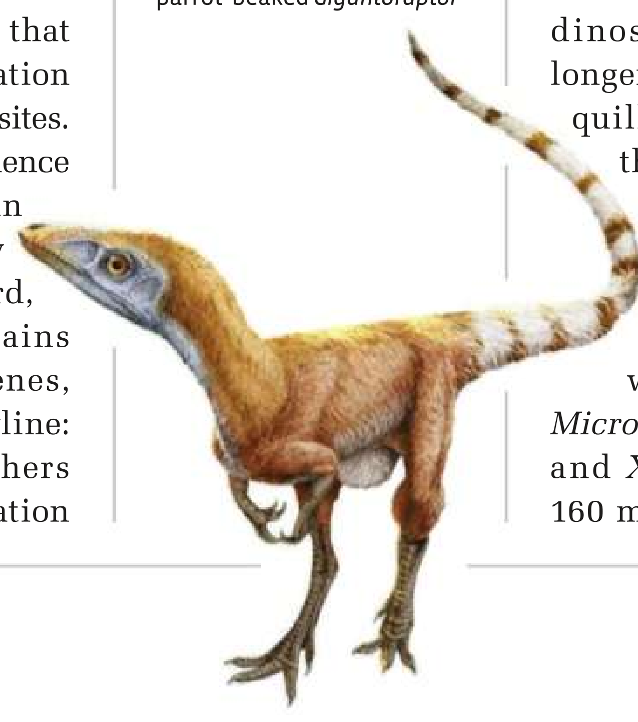


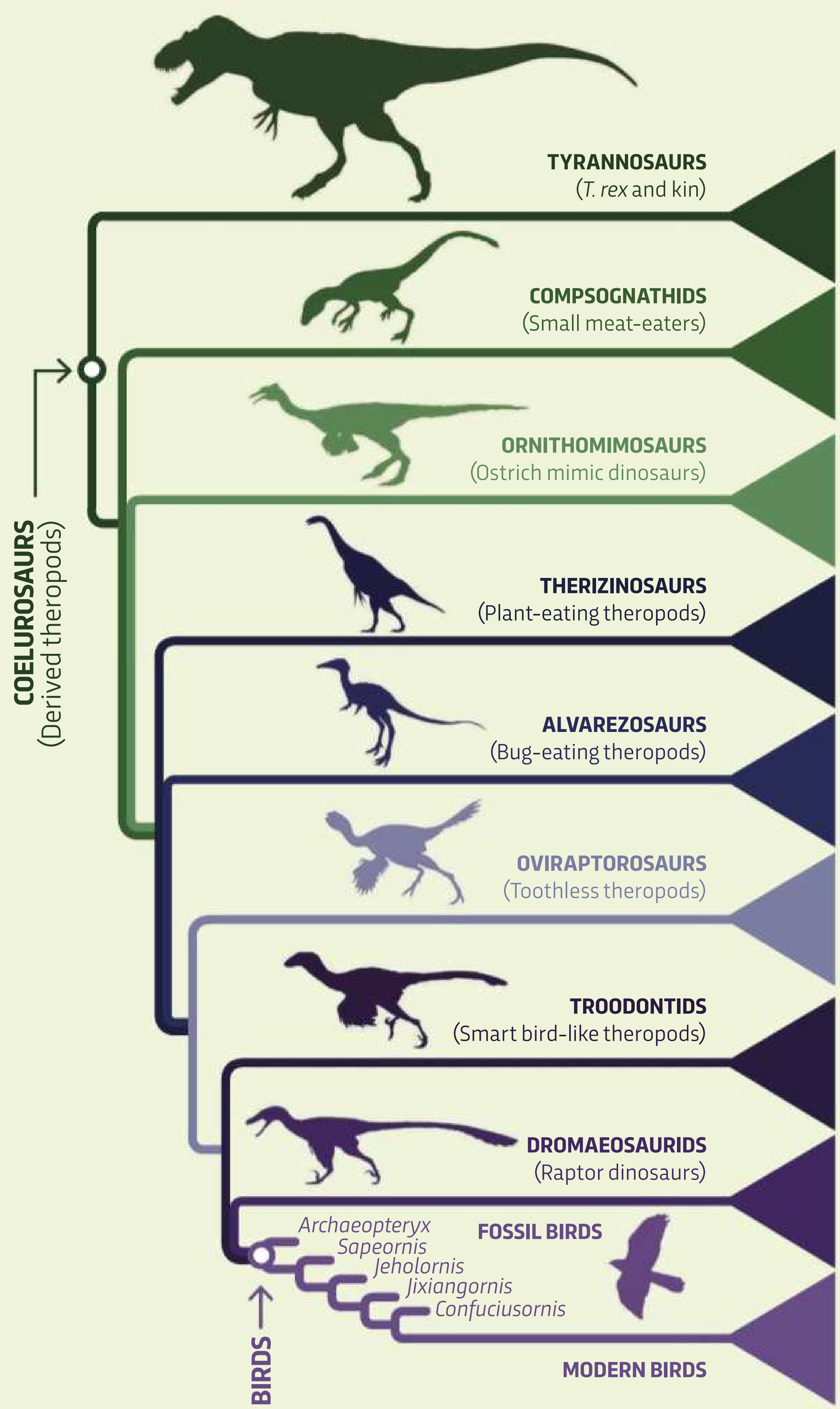
Sinosauropteryx, for example, had a downy fuzz used to keep it warm, which is likely the purpose of the very first feathers to evolve. Over time, these feathers became useful for display too, such as in the 8m-long, parrot-beaked *Gigantoraptor*. This ‘oviraptorid’ dinosaur lived 80 million years ago in what is today the Gobi Desert of Mongolia, and may have used great fans of feathers on its tail and forelimbs for mating displays, like a modern peacock.

“Only later on, when the raptor-type dinosaurs got smaller and their arms got longer, did these feathers elaborate into the quill pens that formed a wing and enabled these animals to fly,” adds Brusatte. They may have been species that scampered between the trees, originally climbing and jumping, and then gliding.

Some of the first were likely four-winged flying dinosaurs similar to *Microraptor*, and its close relatives *Anchiornis* and *Xiaotingia*, which both lived around 160 million years ago in the late Jurassic,

DINO-BIRD FAMILY TREE

Dr Steve Brusatte and colleagues analysed 850 body features in 150 extinct species to create this detailed family tree of meat-eating dinosaurs. It reveals how familiar modern-bird features, such as feathers, wings and wishbones, evolved one by one over tens of millions of years.



"THERE WASN'T ONE MOMENT WHERE *T. REX* MUTATED INTO A CHICKEN. IT WAS A LONG JOURNEY"

shortly before *Archaeopteryx*. While these dinosaurs and *Archaeopteryx* were possibly capable of flapping flight as well as gliding, they were probably not very adept at it, as they lacked a keeled sternum to which large flight muscles are anchored in birds today.

The four-winged model was one early experiment in flight within the group of dinosaurs from which birds evolved, and many early birds also had large feathers on their legs and feet, as some chickens do today.

TEST FLIGHTS

But there were also some other weird experiments in flight at about this time. *Yi qi*, revealed in 2015, was a feathered dinosaur that had large flaps of skin for wings, much more like a modern bat than a bird. This species, and a number of others that had strangely elongated fingers, such as *Epidexipteryx*, may all have been strange dino-bats, but only the discovery of more complete fossils will allow us to know for sure.

What we do know is that feathered dinosaurs and birds were contemporaries, and that species such as *Tyrannosaurus* would have lived in a world that was full of a wide variety of both flying and feathered dinosaurs and their close relatives, the birds.

We also now know that many of the traits that once defined birds actually evolved in their dinosaur ancestors – things such as beaks, highly efficient lungs, excellent colour vision,

A fossil of *Yi qi* showing its elongated fingers

fast metabolisms and lightweight skeletons filled with air pockets that were perfect for flight. The ways in which modern birds nest, brood their eggs and care for their chicks were also shared with some theropod dinosaurs. Research published in the journal *Nature* in late 2018 even revealed that dinosaurs had a variety of coloured and speckled eggs, just like modern birds.

The distinction between a non-avian dinosaur and a bird has become utterly blurred and largely arbitrary.

"There wasn't a moment when a *T. rex* mutated into a chicken, but rather a long evolutionary journey," says Brusatte. "It was a gradual process in which this one lineage of meat-eating dinosaurs one-by-one evolved the characteristic features of today's birds." **SF**

DIAGRAM BY DR STEVE BRUSATTE, DINOSTAR CO LTD, ZHENG XIAOTING, GETTY IMAGES

ABOVE: An artist's impression of 'dino-bat' *Yi qi*

ABOVE RIGHT: Swallow-tailed bee-eaters in South Africa

Listen to an episode of Frontiers discussing dinosaur discovery bbc.in/2N5asEo

Why did some birds survive?

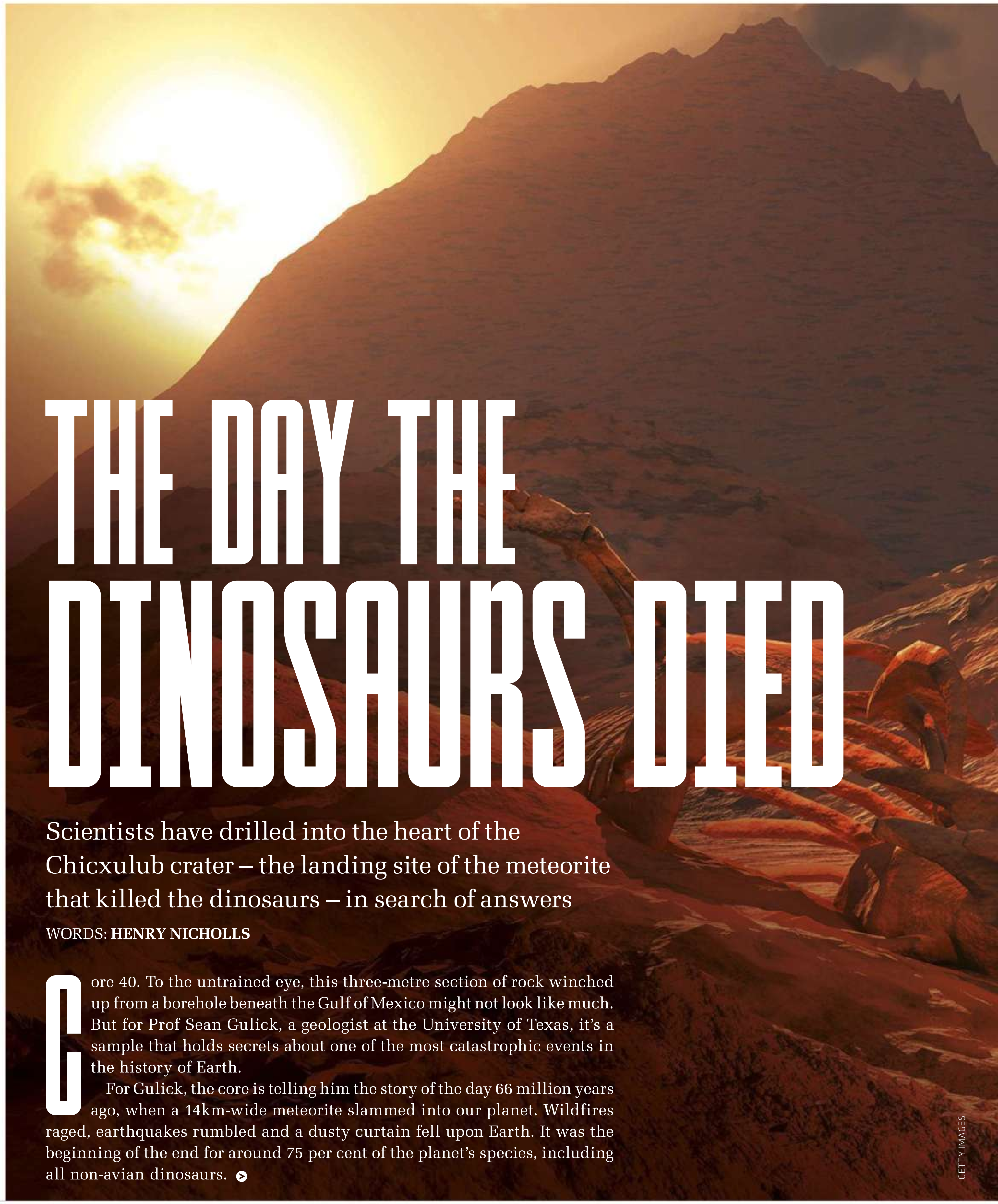
The impact of an asteroid 66 million years ago at the close of the Cretaceous, led to a planet-wide cataclysm that killed up to 70 per cent of all species. No animal larger than 25kg survived. The reasons that birds made it through, while all other dinosaurs did not, is an active area of debate.

Some palaeontologists argue that beaks allowed birds to survive on seeds and nuts (as they could crack them open), which were a remaining source of nourishment after vegetation was incinerated. Others suggest that flight allowed birds to travel far and wide on the search for food in the post-apocalyptic world.

A study published in the journal *Current Biology* in June 2018, revealed that even the majority of bird species alive in the Cretaceous perished. All perching birds that lived in the trees at this time may have died out in the wake of the total destruction of forests in global wildfires.

Instead, the authors argue, all tree-dwelling birds today are descended from ground-living species that managed to survive the extinction.

by JOHN PICKRELL *(@john_pickrell)*
John is a Sydney-based writer and author of **Flying Dinosaurs** *and* **Weird Dinosaurs**.



GETTY IMAGES

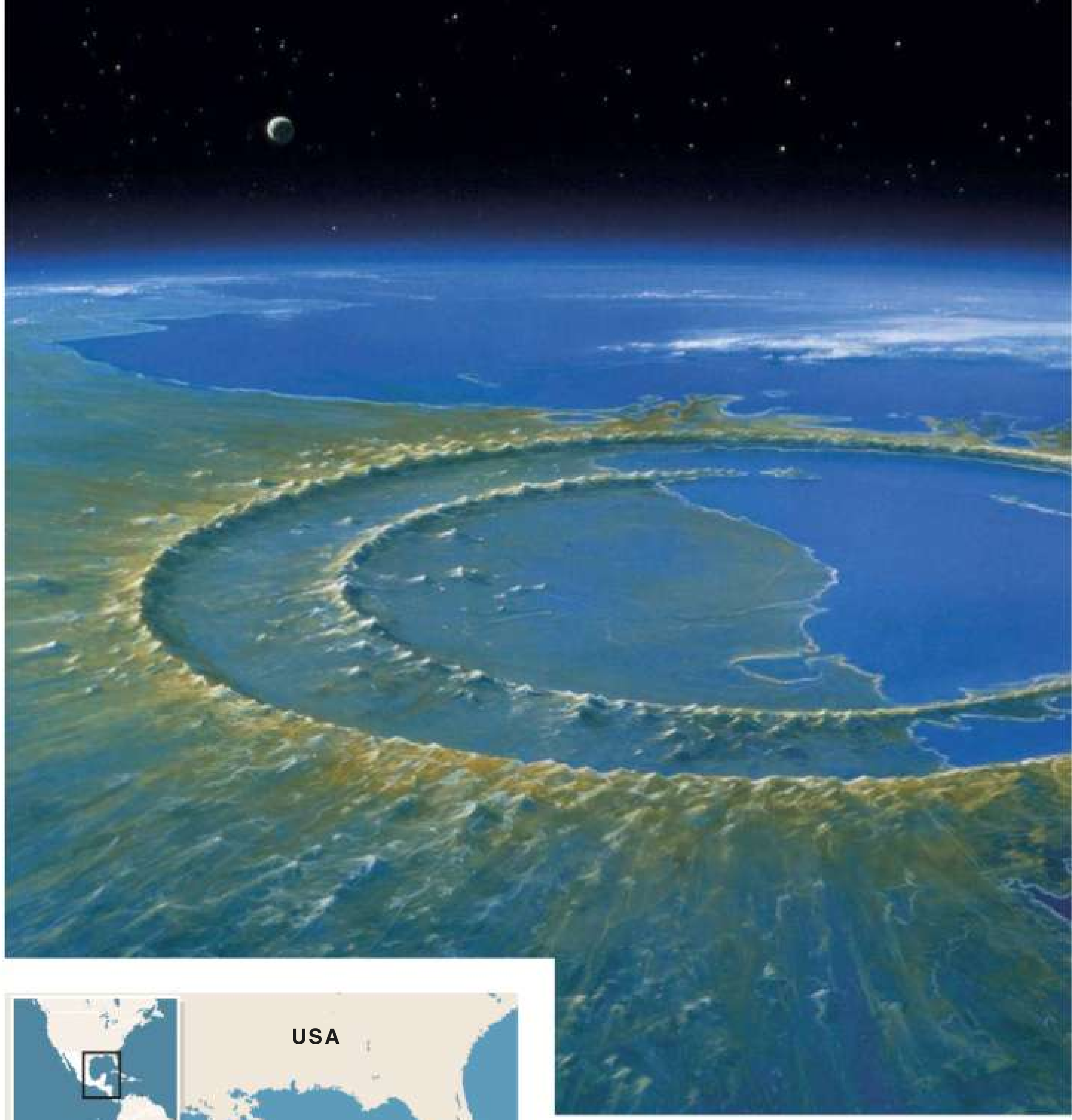
THE DAY THE DINOSAURS DIED

Scientists have drilled into the heart of the Chicxulub crater – the landing site of the meteorite that killed the dinosaurs – in search of answers

WORDS: **HENRY NICHOLLS**

Core 40. To the untrained eye, this three-metre section of rock winched up from a borehole beneath the Gulf of Mexico might not look like much. But for Prof Sean Gulick, a geologist at the University of Texas, it's a sample that holds secrets about one of the most catastrophic events in the history of Earth.

For Gulick, the core is telling him the story of the day 66 million years ago, when a 14km-wide meteorite slammed into our planet. Wildfires raged, earthquakes rumbled and a dusty curtain fell upon Earth. It was the beginning of the end for around 75 per cent of the planet's species, including all non-avian dinosaurs.



Travelling at 20km per second when it entered Earth's atmosphere, the meteorite left a crater 200km across when it smashed into the planet. Today, this geological scar lies buried beneath the Yucatán Peninsula in south-eastern Mexico and Gulick has drilled into its heart.

Throughout April and May in 2016, Gulick was stationed on a drilling rig 30km off the Yucatán Peninsula. He was the co-chief scientist on Expedition 364, the joint project by the International Continental Drilling Program and International Ocean Discovery Program to drill down into the Chicxulub impact crater. On this drilling rig, his team bored down 1.3km beneath the seabed to extract cores of rock.

Since the cores were cracked open in late 2016, geologists, physicists, chemists and biologists have been using what they've found inside to piece together what happened in the minutes, hours, days and years after the meteorite hit.

DRILLING TO DOOMSDAY

Core 40 is special because this section may help explain how one asteroid (or comet) could have had such lethal and far-reaching consequences across the entire planet, but also how life was able to recover following the impact. The preceding 39 cores the team pulled out stretched from 500m to 620m below the seabed. "Then suddenly we hit a layer with fragments in it," says Gulick.

They had found the top of a thick blanket of 'breccia', a jumbled layer of the shattered, melted and traumatised debris that settled immediately after impact. "I didn't expect it to be this nice, sharp transition from limestone [then…] boom, right into angular material with melt in it," says Gulick.

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TIMELINE

A planet in shock

Earth in the hours, years and millennia after the impact

HOURS
Huge earthquakes, megatsunamis up to 300m high, winds of over 1,000km/h and rampant wildfires result in instant annihilation for many species.

WEEKS
Dust from the impact and soot from wildfires block out sunlight for many years. Plants that survived the impact soon struggle. Food webs start to unravel.

YEARS
Prior to the impact, non-avian dinosaurs are already in decline, but the impact seals their fate. If any species survive the impact, it's not for long. Over 90 per cent of all mammal species also go extinct. The largest mammals are hardest hit; the survivors are all smaller than a cat. On land, forests and flowering plants struggle with the low light levels, resulting in a preponderance of species like ferns, algae and moss.

ABOVE: An artist's impression of the Chicxulub crater shortly after impact. The inner 'peak ring' is where scientists are focusing their efforts today

FAR LEFT: The drill site lies 30km off the coast of Mexico

LEFT: Expedition 364 set up a scientific platform in the ocean and spent April and May of 2016 drilling into the seabed to extract core samples from the Chicxulub impact crater

THE METEORITE LEFT A CRATER 200KM ACROSS WHEN IT SMASHED INTO THE PLANET

Of particular interest are the microfossils that sit just above this breccia, which paint a vivid picture of the local conditions in the aftermath. One of those given the responsibility of studying these fossils was Chris Lowery, a post-doc in palaeontology at the University of Texas.

"I've lain awake at night sometimes, wondering what we've got in core 40," he enthuses. "This is the kind of thing I got into science to do. It's so cool to be part of something like this."

Lowery's expertise is in foraminifera, single-celled creatures that often boast beautifully complex internal shells, or 'tests'. By studying the chemical make-up of these fossilised structures, he's attempting to reconstruct the temperature, salinity and local productivity of the water that filled the crater, giving an insight into the kind of environment that survivors of the asteroid would have faced.

Based on work elsewhere, we know that the asteroid impact led to the extinction of more than 90 per cent of all floating, plankton-like foraminifera. The lifeforms that survived were typically small and generalist, but within 100,000 years they had diversified into dozens of different species. "It's exciting to see here, at ground zero, what the properties of the ocean were that might have driven that evolution," says Lowery.

Meanwhile, analysis of the carbon isotopes in the rock core are helping us to understand how the carbon cycle was affected by the impact. This, in turn, is telling us more about the response of the world's plants to the event – and the dinosaurs that depended on them. Similar analysis has been carried out elsewhere, but the Chicxulub cores contain large amounts of material, so it should be possible to build up a more accurate picture of the events that led to a mass extinction.

LIFE DOWN BELOW?

There might even be signs of life in the rubble-like breccia and beneath – microorganisms that have been living and evolving deep underground for millions of years.

"Most of life on Earth is underground," says Charles Cockell, an astrobiologist at the University of Edinburgh. "Something like a massive asteroid impact that killed off the dinosaurs would also have dramatically disrupted the deep biosphere, particularly at the place of impact," he says. "But it may not necessarily have been all bad."

A little over a decade ago, Cockell was part of a similar project in Chesapeake Bay in Virginia on the east coast of the United States, the site of a smaller and, at 35 million years old, more recent impact. This event appears to have fractured the underlying rock, improving the flow of water

300,000 YEARS
Because mammals from several different groups survived, mammal diversity recovers quite quickly, soon doubling the number of species before the extinction.

1 MILLION YEARS
Deciduous trees, reliant on wind pollination, begin to return. Evergreens, which rely on insects and animals for reproduction, take longer to bounce back.

3 MILLION YEARS
In the oceans, there is a rapid flourishing of the plankton-like floating foraminifera. This contributes to the recovery of most marine systems.

10 MILLION YEARS
The surviving reptiles are quick to diversify, with the appearance of iguanas, monitor lizards and boas. Many insect lineages survive the impact. After the event, ants and termites increase in their diversity. Butterflies, too, spread their wings.

15 MILLION YEARS
In a few million years the ancestors of most modern birds undergo a rapid evolution into the multitude of lineages and thousands of species we see today.

WHAT REALLY KILLED THE DINOSAURS?

In 1980, Nobel Prize-winning physicist Luis Alvarez and his team discovered a thin layer of iridium blanketing Earth at precisely the moment when the dinosaurs disappeared from the fossil record. As iridium is one of the rarest elements in Earth's crust, but is found in asteroids in far higher concentrations, they imagined vast quantities of dust (including extraterrestrial iridium) were propelled high into the stratosphere and distributed worldwide.

"The resulting darkness would suppress photosynthesis," they wrote in *Science*, which would have led to the rapid collapse of food webs and the demise of the dinosaurs. A decade later, in 1990, geologists identified Chicxulub in the Gulf of Mexico as the most likely site of this iridium-spreading impact.

Few scientists now dispute the terminal consequences of the Chicxulub event for many species, but there is also evidence to suggest that other factors could have been part of the dinosaurs' demise. The Deccan Traps, in what is now central India, are one of the largest volcanic features on Earth. There is some uncertainty over exactly when they formed – it could have been just before the asteroid impact or as a result of the aftershock – but the volcanic gases released would have had a chilling effect on the climate. It seems likely that the Chicxulub impact would also have triggered a wave of events, like earthquakes, megatsunamis, wildfires, volcanism and acid rain, that could all have helped push Earth's reptilian rulers over the edge.

Dust from the impact cloaked the planet in darkness, leading to the widespread collapse of food webs

THE DEEPER CORES SHOULD HELP ACCOUNT FOR THE FORMATION OF THE PEAK RING

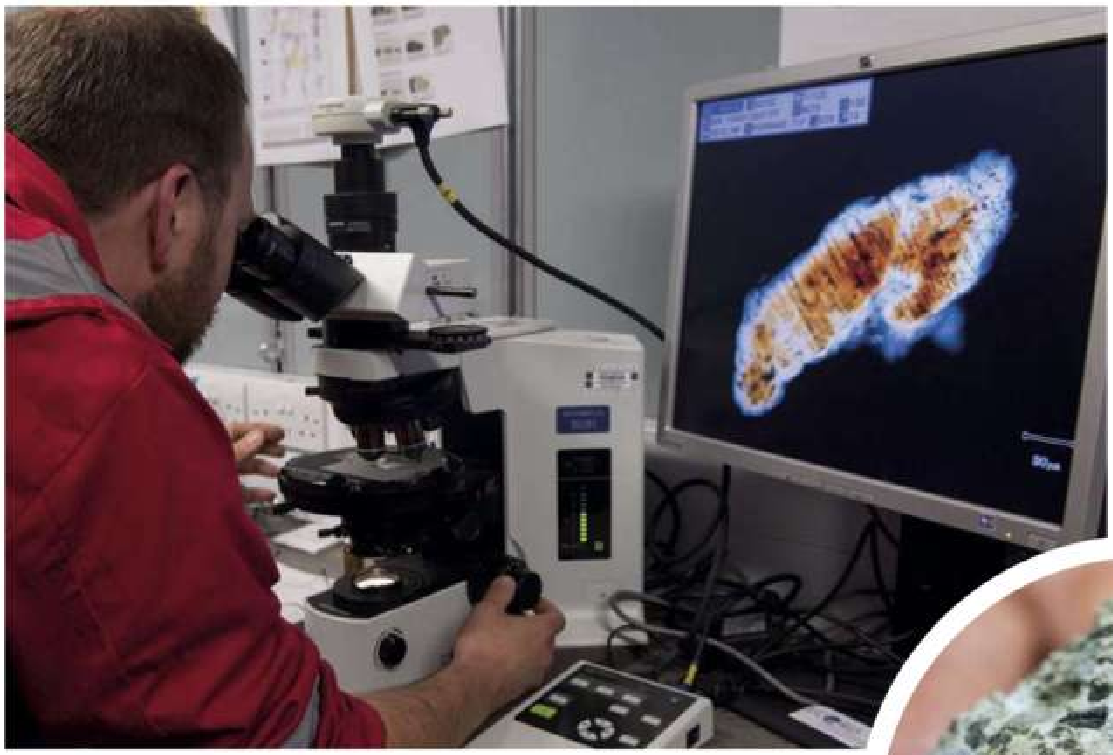
and creating a habitat that would have been particularly suited to microbial life. "What we found there was an increase in the numbers of microbes in impact-fractured rocks."

A similar thing may have occurred at Chicxulub, with the molten rock created by the impact setting up a hydrothermal system that was suitable for life. "The breccia is almost like chicken soup for microbes," says Cockell. "It's got everything in it that's leaching out and providing food for microbes."

Further down, in the underlying granite, the trauma caused by the impact may have created new opportunities for microorganisms. "At the immediate point of impact, everything would have been sterilised, so it was certainly bad for them in the same moment it was bad for the dinosaurs," he says. "But in the longer term, it will have improved conditions for life."

Through analysis of the cores, the researchers are homing in on the date at which the hydrothermal system cooled down enough to allow the microbes to use the chemicals dissolved in the hot fluids for fuel. Earth's magnetic field flips every few hundred thousand years. At the time of the Chicxulub extinction event, the magnetic field had the reverse polarity to that of today. But samples of rock with both 'normal' and reverse polarity were found within the core. As the polarity is 'recorded' by molten rock as it cools, this suggests that the rock at ground zero remained fluid until the field flipped around 300,000 years after impact.

If the researchers' model is correct then it implies that any impact crater could have



ABOVE: The tiny grain of 'shocked quartz' seen on the screen was taken from the Chicxulub impact crater – the dark dots running across it are deformations that occurred when the meteorite hit

RIGHT: A clump of breccia recovered from the Chicxulub impact crater

been a suitable spot for the origin of life on Earth more than 3.5 billion years ago. Though the conditions at the time of the Chicxulub impact were "radically different" from those on the early Earth, says Cockell, the subsurface microbial ecosystem under the Gulf of Mexico could hint at some of the biochemical challenges that the first lifeforms would have faced. In time, the rock cores will likely reveal more secrets about how microbes were able to adapt to the conditions in the breccia.

GOING DEEPER

In the days before drilling began, there was a lot of nervous excitement among the scientists involved. "I was super stressed before I got on the platform," admits Prof Joanna Morgan, a geophysicist at Imperial College London and co-chief scientist of the expedition along with Gulick. But as soon as the cores began to come out of the ground, the stress vanished, she says.

That's not to say everything went smoothly. Early in the project, a 200m piece of piping fell to the bottom of the hole, putting a complete stop to drilling. "The whole thing was a good week of nail-biting before we actually got the first 50-million-year-old core just below that point," says Gulick.

But apart from this glitch, everything went pretty much to plan, with cores being extracted 24 hours a day, seven days a week. "Sometimes we would succeed in coring 30m a day," says Gulick. When the money ran out and it was time to withdraw the drill at the end of May, the hole stretched 1,335m below the seabed.

The deeper cores are of special interest to geologists like Gulick and Morgan, as they should help account for the formation of the so-called 'peak ring', a circular mountain range that lies within the crater, roughly halfway between the centre and the rim. According to Gulick, we can also see structures like this on the Moon, Mercury and Mars, "but we haven't gone and got those rocks," he says.

At Chicxulub, on the other hand, the scientists have drilled right into the peak ring. "It's the only well-preserved large impact on Earth, so we can test the fundamental ways that impact cratering affects a planet," he explains.

The prevailing model to explain this mountainous ring is that, following the impact, there was some kind of rebound of fractured rocks at the centre of the crater, which rippled outwards before eventually coming to a stop. To picture this, think of what happens when you throw a stone into a pond.

Superficially, the rock in these deeper cores looks just like normal granite, says Morgan. "Except, when you look closely, it's highly fractured," she says. "It has a strange set of physical properties. I think it's going to explain to us how rocks that are really hard are weakened enough to be able to move many kilometres during this impact event."

The cores, and all the valuable clues they contain, are being analysed in detail – and some of the early results are in. They suggest that the hydrothermal system generated by the impact was not strong enough to prevent life re-colonising the seafloor relatively quickly.

If the rest of the studies being carried out on the contents of core 40 yield similar insights, we'll have a much clearer understanding of how the asteroid impact affected our planet – and the life on it. SF

by HENRY NICHOLLS *(@WayOfThePanda)*
is a science writer and author of ***Sleepyhead: Narcolepsy, Neuroscience and the Search for a Good Night****.*

THE FIRST MAMMALS

by HAYLEY BENNETT (@gingerbreadlady)

SCIENTISTS RECKON THERE ARE AROUND **6,400 SPECIES OF MAMMAL LIVING ON EARTH TODAY** AND AT LEAST ANOTHER **100 THAT HAVE GONE EXTINCT** IN THE LAST 500 YEARS. THEY RANGE FROM THE 5CM-LONG **AUSTRALIAN PYGMY POSSUM** (ABOVE), WHICH USES ITS TAIL TO HANG UPSIDE DOWN FROM TREES, TO THE **IRRAWADDY DOLPHIN**, WHICH HANGS OUT IN THE LAGOONS AND MANGROVE FORESTS AROUND THE COAST OF INDIA. YET **ALL LIVING MAMMALS ARE DESCENDED FROM ONE SMALL GROUP OF LIZARD-LIKE ANIMALS** THAT EMERGED JUST BEFORE THE 'GREAT DYING', THE PERMIAN-TRIASSIC MASS EXTINCTION THAT OCCURRED 251 MILLION YEARS AGO. **SO HOW DID WE GET TO HERE?**

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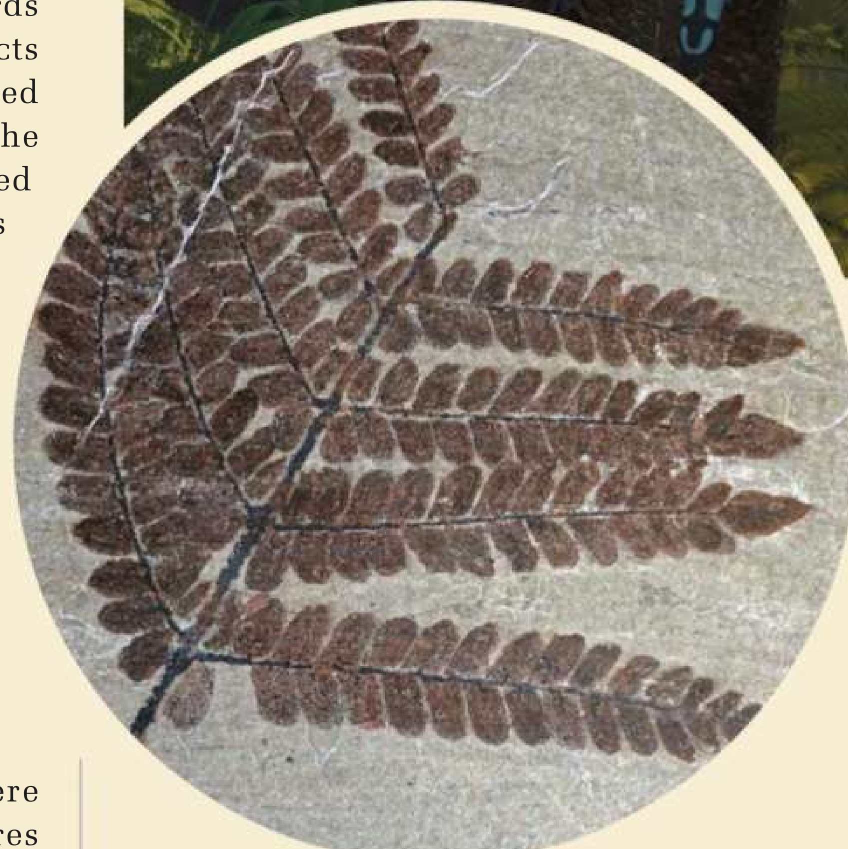


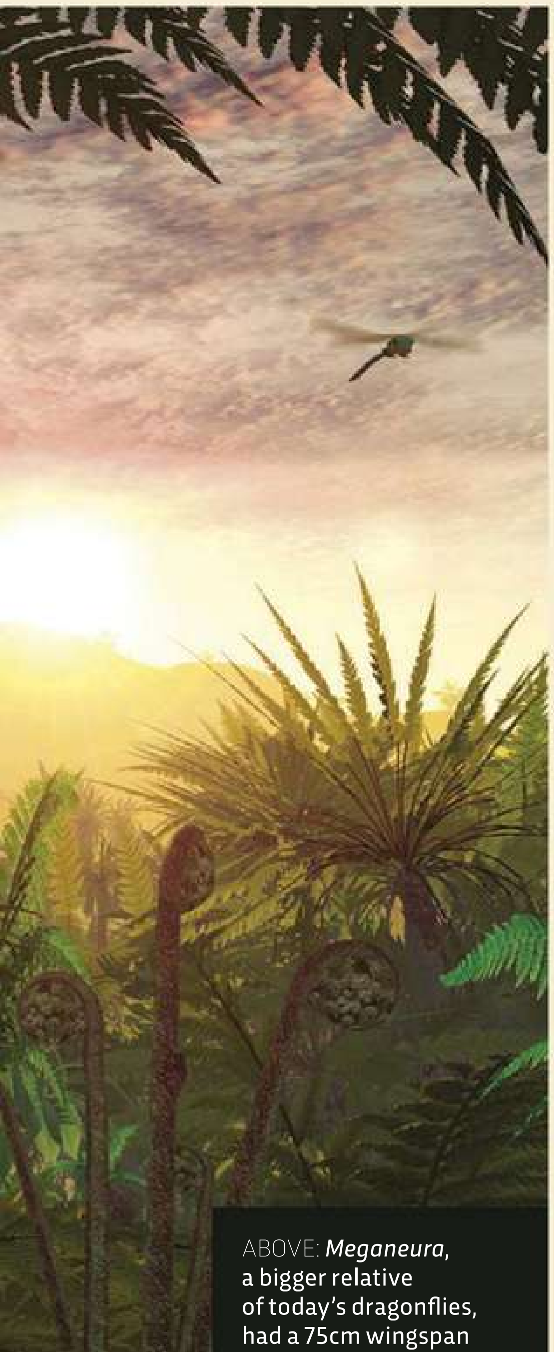
The coal that fuels our energy-hungry world was formed at the end of the Carboniferous Period, when the Earth was a little warmer than it is today (the global average was estimated to be about 20°C)and covered in swampy forests. Armoured fish swam in the oceans, lizards and crocodiles stalked the land, and insects flourished – some giant millipedes reached the size of large sheep. By the end of the Carboniferous, the temperature had cooled down to approximately 12°C and new kinds of four-limbed creatures emerged in the drier conditions.

The first synapsids, the ancestors of mammals, date to around 310 million years ago. Although these tetrapods appeared reptilian, they were not descended from them. Reptiles branched off in an altogether different direction on the evolutionary tree. Equally, though, they were not yet mammals. So what were they?

TEETH AND LEGS

In their most primitive form, they were pelycosaurs – small, low-profile creatures that looked like lizards, right up until they opened their mouths, which contained the beginnings of mammalian canine teeth. It is thought that some of the traits we see today in mammals, such as parental care, originally surfaced in this group and gradually advanced in the therapsids (animals whose limbs grew vertically underneath their bodies rather than sprouting horizontally outwards, like those of reptiles) that evolved at least 270 million years ago.

Along with birds and crocodiles, therapsids became the dominant land vertebrates following the 'Great Dying'. The most mammal-like therapsids – the cynodonts – which appeared roughly 260 million years ago, were limited in range before this mass extinction, but expanded rapidly afterwards. Some of these animals still laid eggs, but from fossils it's unclear if they had fur. They did, though, have skulls and jaws more similar to modern mammals.



ABOVE: *Meganeura*, a bigger relative of today's dragonflies, had a 75cm wingspan

FAR LEFT: Plant fossils, like this one found in New Mexico, USA, show ferns were abundant in the swamps of the Carboniferous period

LEFT: A fossilised segmented worm (*Didontogaster cordylina*)

BELOW LEFT: Prehistoric millipedes grew to much larger sizes than their current descendants

BELOW: *Cynognathus*, a cynodont therapsid, grew to approximately a metre in length

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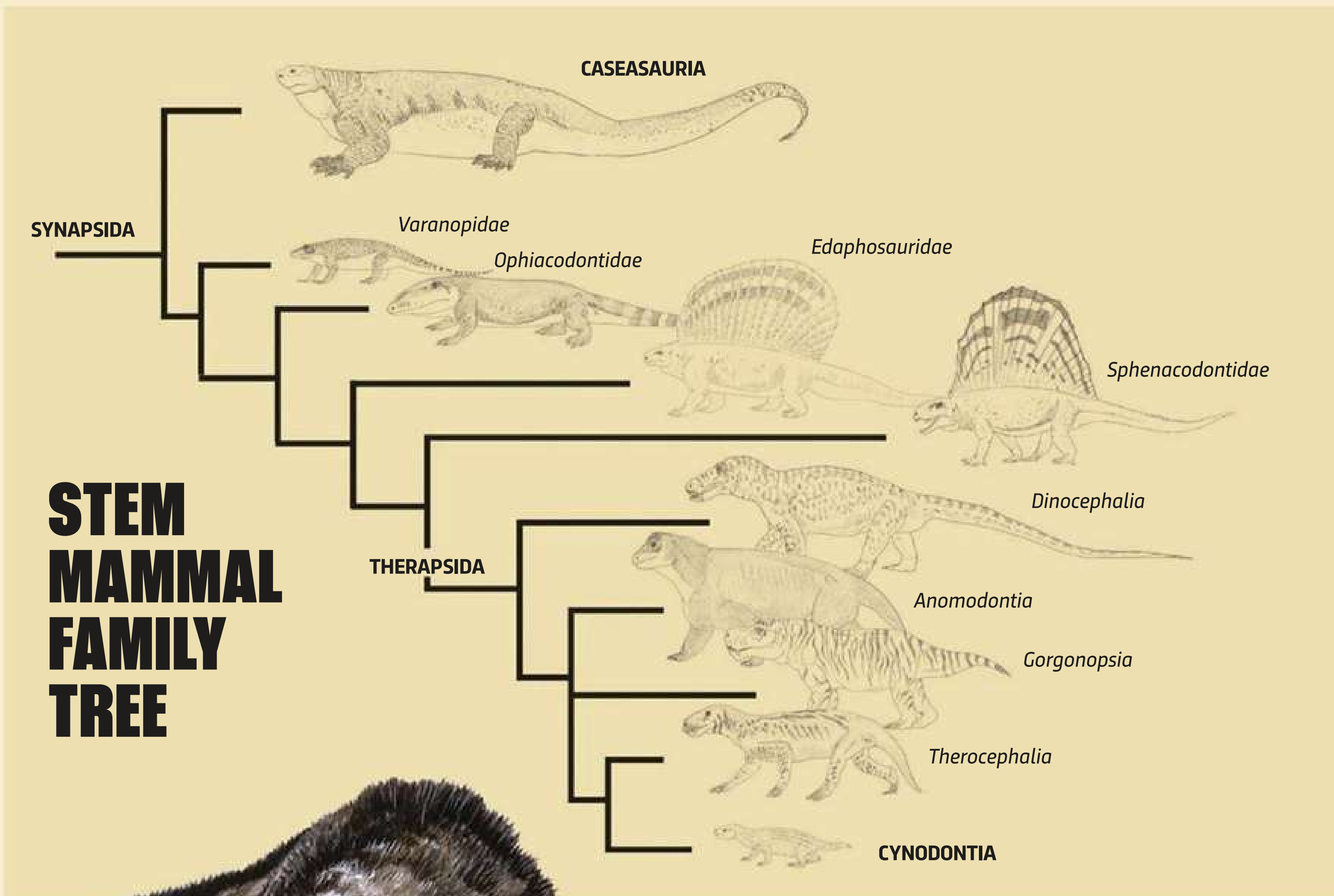
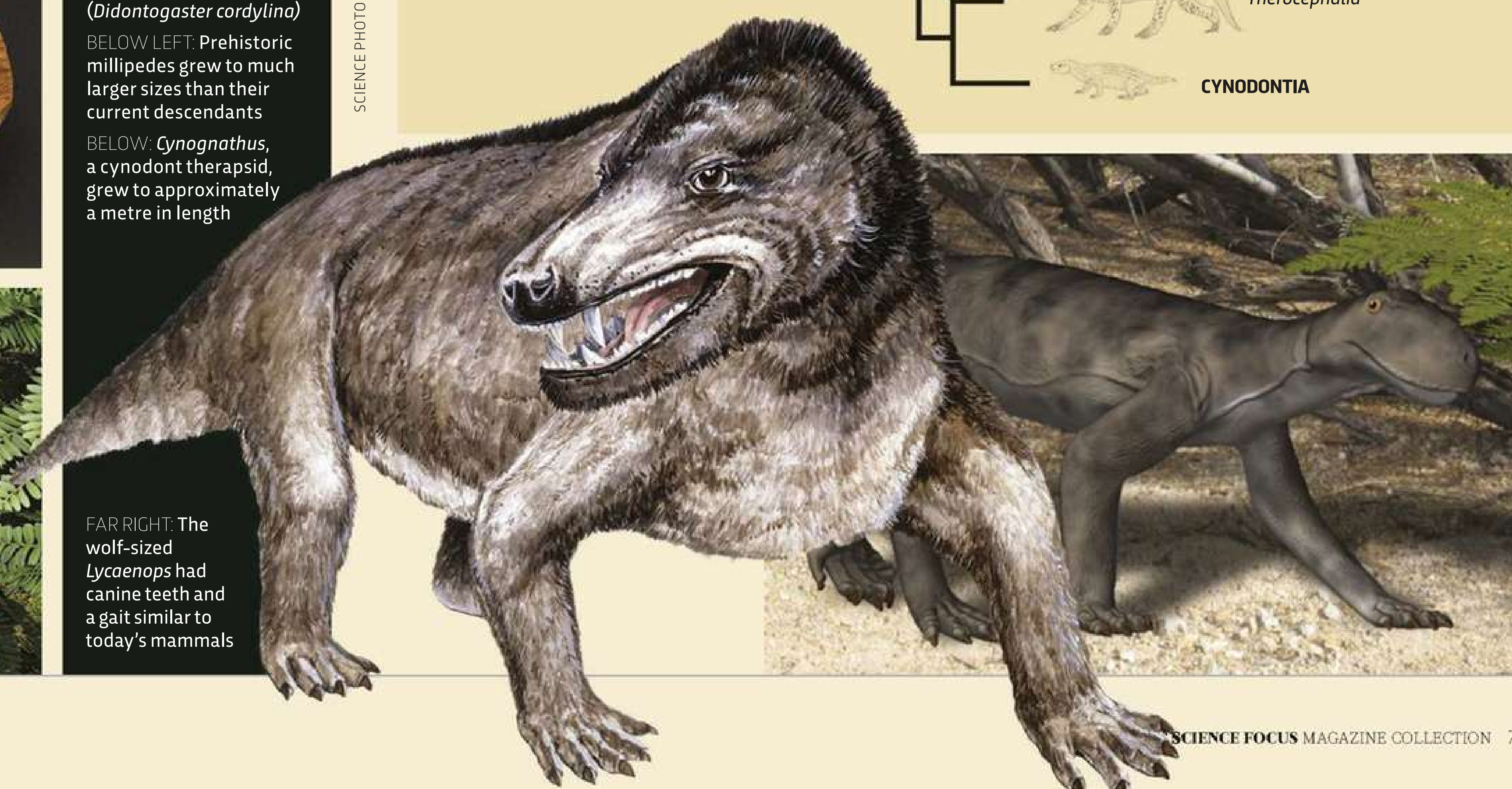
ALTHOUGH THESE TETRAPODS APPEARED REPTILIAN, THEY WERE NOT DESCENDED FROM THEM

STEM MAMMAL FAMILY TREE





FAR RIGHT: The wolf-sized *Lycaenops* had canine teeth and a gait similar to today's mammals

Mammals that looked like reptiles

❶ Not a dinosaur
Illustrations of the 280 million-year-old, sail-backed pelycosaur, *Dimetrodon*, would have you believe it was a dinosaur. But with its specialised teeth, large brain and three middle ear bones rather than one, the contents of *Dimetrodon*'s skull distinguished it from its reptilian cousins.

❷ Sabre-toothed proto-cats
Discovered in 2018, by fossil hunters in western Russia, *Gorynychus masyutinae* was a wolf-sized therapsid with enlarged canine teeth, making it a dangerous predator. It is thought to be from the period just before the 'Great Dying', when therapsids thrived and some larger species, like *Gorynychus*, shot to the top of the food chain. *Gorynychus* is important to understanding mammal evolution because therapsid fossils are rarely found outside of Africa.

❸ Nearly a mammal
Fossilised bones and teeth from late cynodonts are relatively common finds. But in 2018, palaeontologists unearthed an entire skull in the Cedar Mountain rock formation in Utah. *Cifelliodon wahkarmoosuch*, an unusually large, hare-sized cynodont is thought to be a haramiyidan – a group alternatively placed inside and outside of the mammals, but most recently outside.

❹ Dog teeth
The name cynodont means 'dog teeth', referring to the sharp canine teeth that modern mammals use to pierce and tear – these are present even in plant-eating herbivores. Differentiated teeth, including canines as well as incisors and molars, are found as far back as the most primitive of the synapsids.

❺ Holes in the head
What distinguishes synapsids or early mammal-like animals from reptiles is the number of holes on each side of their skulls. Synapsids had an extra hole behind both eye sockets. These holes probably provided attachment points for jaw muscles and, later in evolution, were filled in by bone, leaving just arches.

❻ Monsoon regions
200 million years ago, instead of the seven continents we know today, there was one giant supercontinent – Pangea. There were also no polar ice caps and few mountains, so animals weren't constrained by geographical barriers. But fossil evidence shows that cynodonts kept to tropical regions where heavy rains fell twice a year, suggesting they needed more water, while reptiles were capable of surviving in drier conditions. ➔

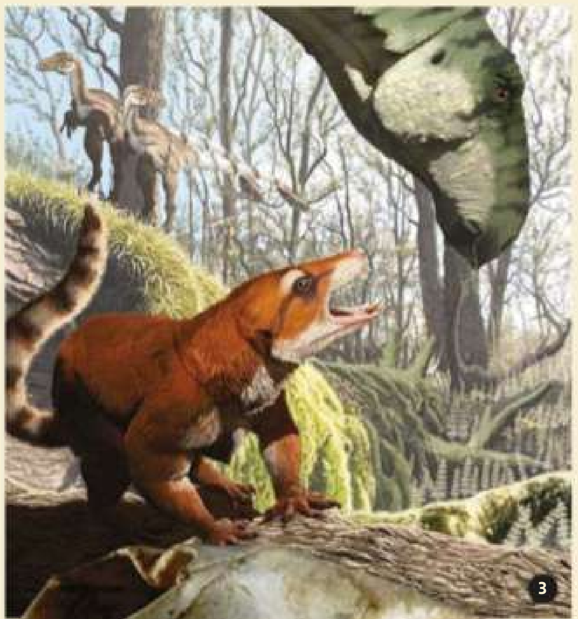
ABOVE: The sail-back *Dimetrodon* might have looked like a dinosaur, but it was in fact a mammal

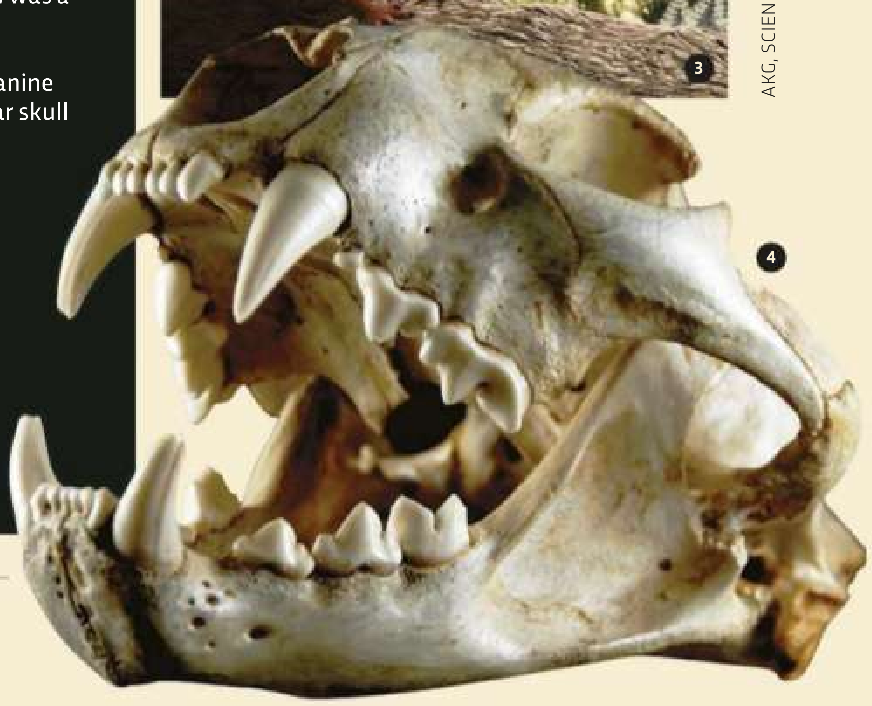
LEFT: The saber-toothed prehistoric predator *Gorynychus Masyutinae*

BELOW LEFT: A *Dimetrodon* skull which shows its specialised teeth

RIGHT: Controversy reigns over whether *Cifelliodon wahkarmoosuch* was a mammal or not

BELOW RIGHT: Canine teeth on a cougar skull





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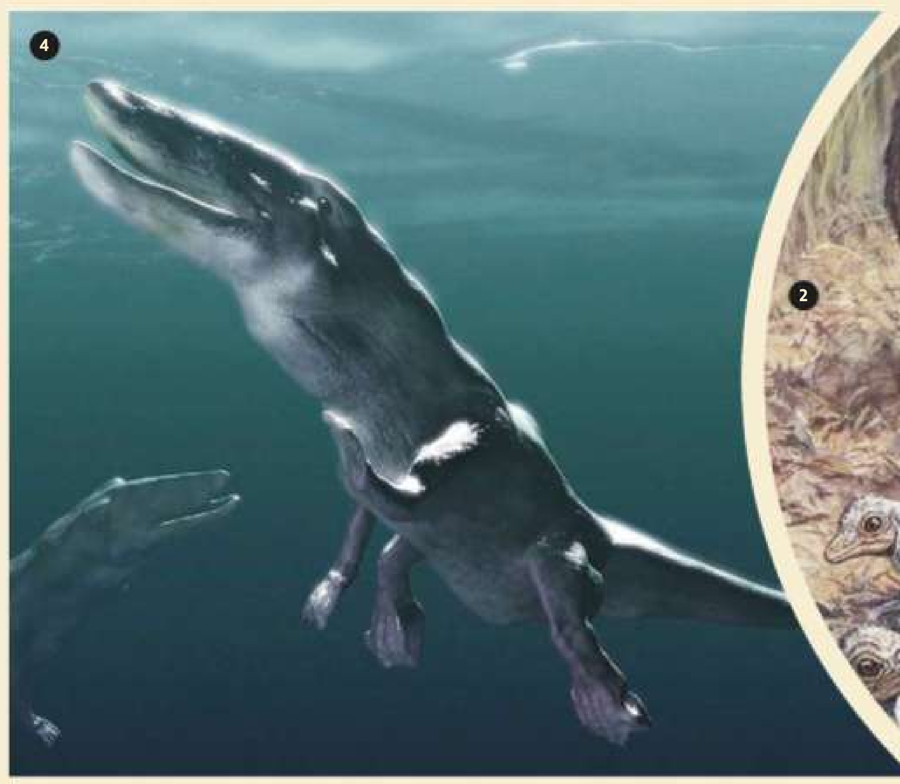
How do we know where we came from?

For centuries, palaeontologists have charted the history of life on Earth by scrutinising and categorising fossils – the remains of animals, plants and microbes preserved in rocks. The study of mammal evolution has progressed, for the most part, by looking at layers in rock formations to estimate how many millions of years ago the animals lived and, when there are enough fossilised remains to go by, comparing their anatomy. Rock layers are accurately dated by radiometric dating, a technique that measures the state of decay of radioactive elements, such as carbon-14, in rocks and uses it to estimate when the rocks were formed.

More recently, molecular biologists have started studying DNA from living mammals to try to reconstruct evolutionary trees based on differences in their genes. Because genetic changes are assumed to occur at a fairly constant rate, DNA can be used as a 'molecular clock' to date the common ancestors of related species. Scientists have used this method to suggest that elephants come from one of the oldest lines of existing ungulates – animals that include horses, camels and giraffes – and that bats have more in common with cows than with flying lemurs.

Rock strata contain a record of geological periods

Early mammals



❶ Jurassic mother

When Chinese palaeontologists uncovered the earliest known mammal in Lianong Province in 2011, they named it *Juramaia sinensis* ('Jurassic mother from China'). This small, furry, 160-million-year-old animal resembled a shrew and pre-dated what was previously the oldest mammal by 35 million years, meaning that mammals were more evolved than we thought during the age of the dinosaurs. The researchers were keen to find out what type of mammal it was. While marsupials like kangaroos and koalas nurse their babies in a pouch until they are able to survive outside, placental mammals give birth to more fully developed babies. (Today's only other surviving branch of mammals – the monotremes – lay eggs, like platypuses.) The placental mammals are sometimes said to be more advanced. But even at this early stage in mammal evolution *Juramaia* showed features that align with placental mammals. The researchers found that its paws and teeth were more similar to animals from this group, although they can't say for sure that it didn't have a pouch, because any pouch tissue would have degraded long ago.

❷ Dinosaur for dinner

130 million years ago, mammals were competing with dinosaurs for food. Some of them survived not by eating the dinosaurs' food but by eating the dinosaurs themselves. *Repenomamus* was a badger-sized mammal with a taste for *Psittacosaurus*. Researchers know this because they found pieces of the dismembered dinosaurs in their stomachs.

❸ Ziggy's tooth

Since teeth take so long to decompose, they are often the only things left to go by, so it's not uncommon for fossil discoveries to be based on dentistry alone. In 2018, Brazilian palaeontologists found the first Brazilian mammal from the era of the dinosaurs – based on a single tooth – and named the new species *Brasilestes stardusti* in tribute to David Bowie's character, Ziggy Stardust. The 80-million-year-old tooth belonged to a large mammal from the class Theria that probably gave birth to live young rather than laying eggs.

❹ Walking whales

Our own ancestors emerged from the sea 400 million years ago and never looked back, but somewhere along the mammal lineage,

TOP: *Juramaia sinensis* was the earliest known ancestor of placental mammals

ABOVE: *Ambulocetus* was known as the 'walking whale'

ABOVE CENTRE: *Repenomamus* feasted on dinosaurs

RIGHT: An Indo-pacific bottlenose dolphin (*Tursiops aduncus*) mother nursing her calf

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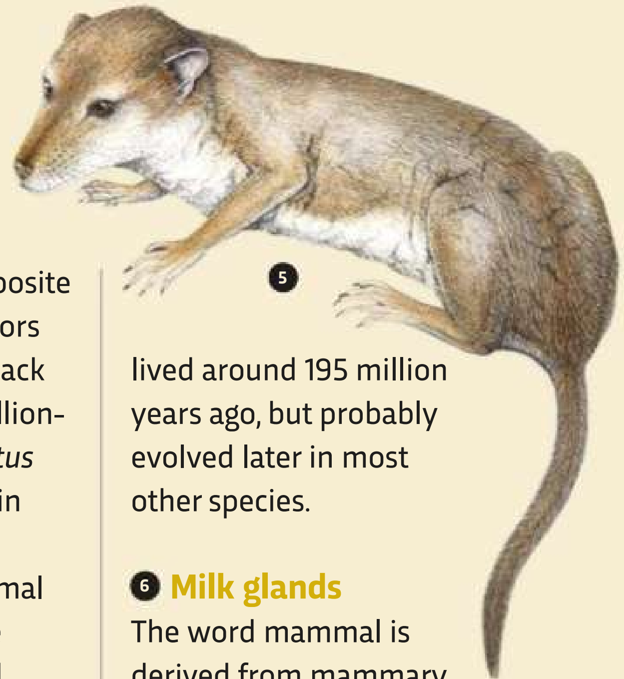


things went the opposite way and the ancestors of whales headed back to the water. 49-million-year-old *Ambulocetus natans*, discovered in 1992, embodies this transition – a mammal from the whale line that could walk and swim, it probably looked like a cross between a crocodile and an otter.

5 Jaw joint

Reptiles' jaws are made up of several bones. But in mammals, the jaw bones fused together early during our evolution to form one piece, the bones that didn't got smaller and moved back to form part of our ears. This separation between our jaws and ears eventually made space in our skulls for bigger brains. These features can be recognised in the mouse-like cynodont *Hadrocodium wui*, which lived around 195 million years ago, but probably evolved later in most other species.

6 Milk glands

The word mammal is derived from mammary glands. All mammals produce milk and use it to feed their young; even bats and dolphins breastfeed. It's thought that ancestral animals had glands that were more like sweat glands (associated with hairs) but because there is no fossil evidence, it is hard to know for sure. Today's platypuses have mammary 'patches' but no nipples, possibly resembling primitive mammary glands.

7 Jurassic forests

During the Triassic and Jurassic periods, the supercontinent Pangaea began to fragment into the modern continents we know today (see right). New oceans and mountains formed and habitats and climates became more varied. In what would become Asia, dense forests were home to gliding mammals the size of modern flying squirrels. At this time, trees were also perches for pterosaurs and feathered dinosaurs that would eventually evolve into birds. SF

Continental divides

PERMIAN 250 MILLION YEARS AGO

TRIASSIC 200 MILLION YEARS AGO

JURASSIC 145 MILLION YEARS AGO

CRETACEOUS 65 MILLION YEARS AGO

BBC FOUR *Watch a clip about a fossil primate called 'Ida' that may be one of our earliest ancestors* bbc.in/2SvmIEd

by HAYLEY BENNETT
Hayley is a science writer based in Bristol.

HOW EARTH MADE US

This powerful planet that we live on has shaped our evolution and determined our destiny

WORDS: **LEWIS DARTNELL**

Humans today, with our global industrialisation and fervent exploitation of fossil fuels and other natural resources, are having an overwhelming impact on the planet. We are now the dominant environmental force on Earth, and many scientists have proposed the naming of a new geological epoch: the Anthropocene, the recent age of humanity.

But this has only recently become the case, the planet that we live on has had a profound influence on our human story. Here, we'll look at how the Earth crafted our own origins as a particularly intelligent species of ape, and then the global conditions that enabled us to disperse around the whole world. And the Earth has not only deeply affected the course of our history, but also that of all the plant and animal species we came to domesticate with the origins of agriculture and the birth of civilisation.

Lake Nakuru in the East African rift valley – our ancestral cradle

GETTY IMAGES

HOW WE EVOLVED

Us *Homo sapiens* are an exquisitely, uniquely, intelligent species. Sure, there are other isolated examples of problem solving, tool use and astonishing communication skills throughout the animal kingdom, such as octopuses, dolphins or crows. But nothing compares to humanity's diverse skill-set. The whole evolutionary tree of human-like apes that we belong to – the hominins – exhibited enlarging brain size and increasingly sophisticated tool use over the past few million years.

Hominins diverged from the chimpanzee lineage about seven million years ago. Since then, hominins became increasingly bipedal, and then more efficient long-distance runners, with changes to our skeleton including an S-shaped spine and bowl-like pelvis. Brain size also increased, and we applied our intelligence to making and using ever-more sophisticated tools – such as stone blades and wooden spear shafts. These sticks and stones became our artificial teeth and claws, allowing us to defend ourselves or be fearsomely effective hunters, all while keeping a safe distance. And all these developments in body form and lifestyle enhanced each other. Efficient running, clever team work, and the wielding of tools and fire enabled our ancestors to hunt more effectively and catch more meat for fuelling a larger brain. This, in turn, drove more complex social interaction and problem solving, and eventually the emergence of language.

All of this evolutionary creativity occurred in our ancestral cradle of East Africa. Every species is crafted by its natural environment it adapts to, so what was it about our evolutionary milieu that made us such an intelligent and behaviourally-versatile ape?

If you look at a map of the Earth you'll notice that around the world's waistline is a broad band of dense vegetation – the equatorial rainforests of the Amazon, central Africa and the islands of the East Indies. Warm, moist air rises along the equator and generates lots of rainfall to water this band of dense forest. By the time this atmospheric circulation has rolled over through high altitude and descended back to the Earth's surface again – at around 30° north and south of the equator – the air has become bone dry. This is where we find two bands of deserts around the planet: the Patagonian Desert in South America, Kalahari in South Africa and Great Sandy Desert of Australia; as well as the mirror-image band in the northern hemisphere: Sahara, Arabian Peninsula and Thar Desert in north-west India.

THE SCENERY OF OUR ANCESTRAL LANDS SHIFTED FROM THAT OF *THE JUNGLE BOOK* TO *THE LION KING*

East Africa, where we evolved, straddles the equator and so it too ought to be smothered with rainforest, just as central Africa is. Instead, it stands out as a little dry corner of Africa. So the primary environmental factor that drove our evolution from tree-swinging apes to bipedal hominins hunting across the savannah was that our environment dried around us and forest gave way to grassland.

One of the planetary processes that drove this transformation was a plume of magma rising beneath East Africa that forced the crust to bulge upwards like a huge spot. The skin of the

ABOVE: The Teles Pires is a 1,370km-long river in the Amazon rainforest in Brazil

RIGHT: Sand dunes and rock towers at Ouan Zaouatan in the Sahara Desert in Algeria

GETTY IMAGES X2

TAMING THE WILD

Civilisation isn't just built on the agriculture of productive crop plants. For millennia we have also relied upon domesticated animals to support us. In fact, the first animal to be tamed by humanity was the wolf tens of thousands of years before we settled down when we were still roaming the ice age landscape.

Farming livestock, rather than hunting wild herds, provides a reliable source of meat and leather, but also enabled the repeated collection of crucial new resources like milk and wool. Domesticated beasts of burden can also be trained to provide their muscle power for transport. Large animals domesticated by humanity are all ungulate species – herbivores which have diversified greatly in the past 20 million years with the spread of the grasslands, as the Earth cooled and dried.

Originally, however, the first appearance of the ungulate orders of animals dates back 55.5 million years to an extraordinary spasm of Earth's climate. The Palaeocene–Eocene Thermal Maximum (PETM) saw temperatures spike by 8°C from a massive injection of greenhouse gases into the atmosphere.

planet tore in a great Y-shape, creating the Red Sea, the Gulf of Aden and a long rent that runs for thousands of kilometres to the south called the East African rift valley. This tectonic feature formed by crustal swelling and ripping has a distinctive form: high ridges of mountains running along either side of a wide valley floor.

EVOLUTION OF INTELLIGENCE

This rift has blocked moisture blowing into East Africa and so caused the whole area to dry out. East Africa was transformed from a densely forested plain into a rugged landscape. The scenery of our ancestral lands shifted from that of *The Jungle Book* to *The Lion King*. But the Great Rift Valley also had a much more direct effect on driving the evolution of intelligence within us hominins.

The mountainous flanks collect the rainwater which runs down to fill lakes on the hot, desiccating valley floor. This makes the water levels of these lakes exceedingly sensitive to even tiny fluctuations in the regional climate and the balance between rainfall and evaporation. These lakes flicker in an out of existence with the rhythm of cosmic cycles in Earth's tilt or its orbit around the Sun – known as the Milankovitch cycles – that affect the climate. It is these periods of rapidly-changing water levels, and thus presence of vegetation and game to hunt, that are thought to have driven the hominin evolution of larger brains and more versatile, intelligent behaviour to survive. So humans were crafted by the combination of the active tectonic landscape of East Africa and cosmic cycles in Earth's tilt and orbit.

HOW WE MIGRATED

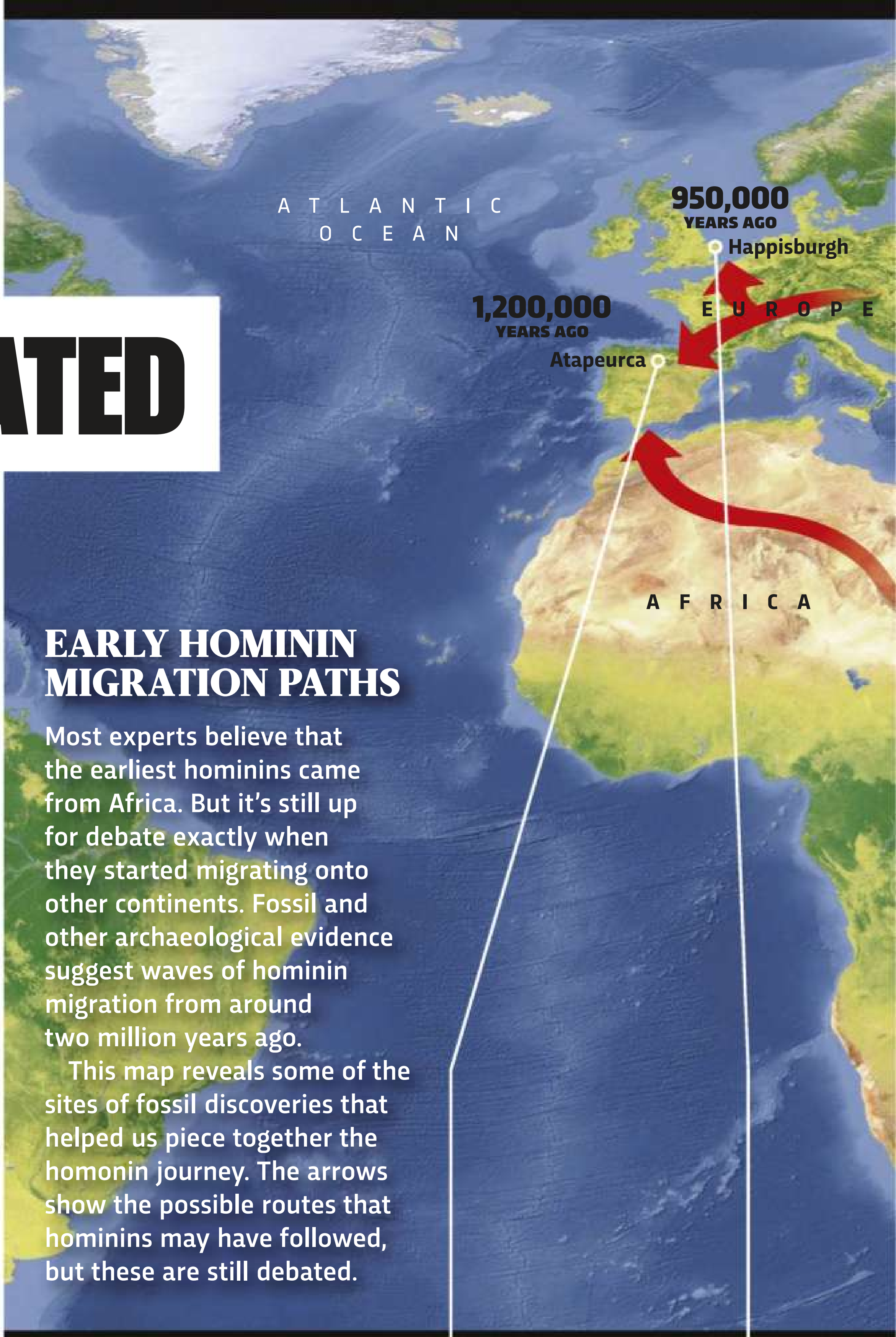
Humanity may have developed in the East African rift valley, but we didn't remain in our cradle. Our ancestors dispersed across every continent of the planet (except for the frozen wastelands of Antarctica) to become the most widely-spread animal species on the planet.

In January 2018, scientists confirmed that a jawbone fossil, which was discovered in Misliya cave at Mount Carmel, Israel, back in 2002, showed that *Homo sapiens* lived outside Africa around 185,000 years ago. This was 80,000 years earlier than previously thought. And yet, tools found in the cave date even further back, suggesting the first exodus of *Homo sapiens* could have been as early as 250,000 years ago. But these early migrations seem to have ended in dead-ends, as DNA evidence shows that modern-day humans living outside Africa only trace their ancestry to an exodus around 60,000 years ago.

ICE AGE INFLUENCE

Our migrating ancestors moved out through the Arabian peninsula and into the huge sprawling landmass of Eurasia. The world back then was a very different place – Earth was in the freezing grips of an ice age. At its peak, immense ice sheets up to 4 kilometres thick extended from the north to smother northern Europe and America, as well as Siberia. Great glaciers also spread down from mountain ranges such as the Alps, Andes and Himalayas, as well as the rugged backbone of New Zealand. As well as being punishingly cold close to the ice sheets, reduced evaporation from the frigid seas also made the world much drier, with howling winds driving fierce dust storms across great arid plains.

Just as the cosmic periodicities of the Milankovitch cycles cause fluctuating aridity in equatorial East Africa, the same cycles drive rhythms in the global climate, and in ➜



EARLY HOMININ MIGRATION PATHS

Most experts believe that the earliest hominins came from Africa. But it's still up for debate exactly when they started migrating onto other continents. Fossil and other archaeological evidence suggest waves of hominin migration from around two million years ago.

This map reveals some of the sites of fossil discoveries that helped us piece together the homonin journey. The arrows show the possible routes that hominins may have followed, but these are still debated.

SIERRA DE ATAPUERCA, ***SPAIN***

Fossils dating back to between 1.2 million and 800,000 years ago have been discovered at two sites. They are either *Homo antecessor* or a branch of *Homo ergaster.*

HAPPISBURGH, ***NORFOLK***

No fossils have been discovered but footprints, possibly made by *Homo antecessor,* suggest it may have been the first hominin to reach Britain.

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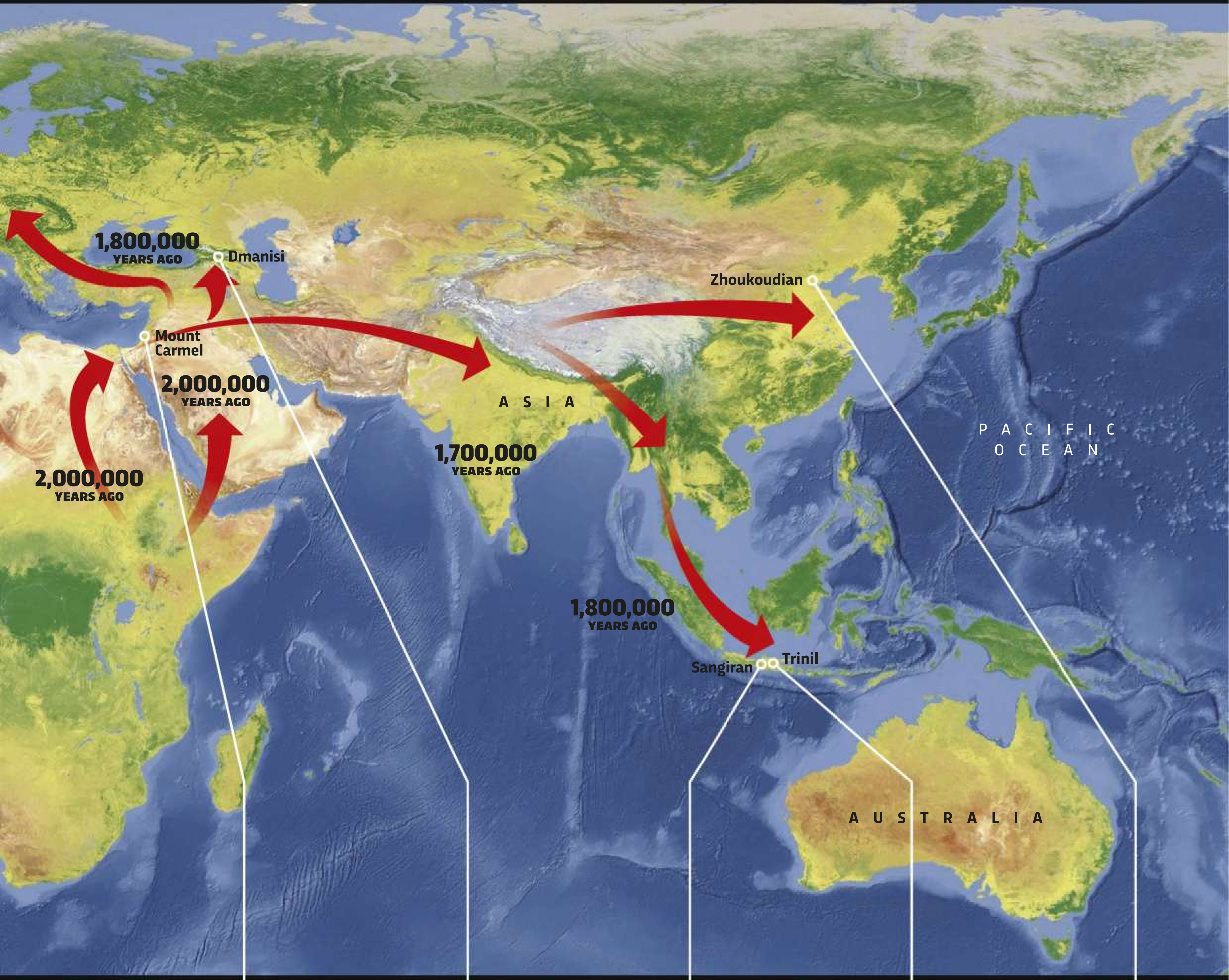

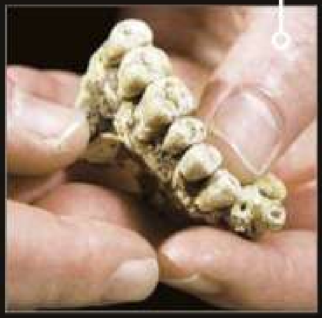

MOUNT CARMEL,
ISRAEL

A jawbone fossil suggests *Homo sapiens* lived outside Africa around 185,000 years ago, yet tools that have been found could push that date back further.

DMANISI,
GEORGIA

Fossils and artefacts were found dating back to 1.7 million years ago. Scientists are debating whether the fossils are of *Homo erectus* or a new species *Homo georgicus*.

SANGIRAN,
JAVA

A *Homo erectus* skullcap, discovered in 1937, was found to be very similar to another fossil found on Java at a site just three hours' drive away in Trinil.

TRINIL,
JAVA

Another *Homo erectus* skullcap was discovered at this site. Its age has been hotly contested – estimated to be somewhere between 1.7 and 1 million years old.

ZHOUKOUDIAN,
CHINA

Fossils of *Homo erectus*, dating back to between 800,000 and 400,000 years ago, were found at this site, and given the nickname 'Peking Man'.

FOOD FOR THOUGHT

Why is it that every morning the majority of us eat a bowl of cereal or slice of toast for breakfast? This isn't a frivolous question, but reaches back to the very dawn of agriculture itself.

The cereal crops that form the staple of all of our meals today – and have supported humanity through the entire history of civilisation – in particular wheat, rice and maize, but also barley, rye, sorghum and oats, are all species of grass. For millennia humanity has thrived by eating grass – we are no different from the cows and sheep we leave out to pasture.

We picked these particular plants as the staples of agriculture because grass species are fast growing, and put all of the energy they harvest from the Sun into their nutritious grain (seeds) rather than, for example, building stout trunks. This is because grasses have become ecologically adapted to rapidly colonising land cleared by forest fires, or surviving in drier environments.

So the global cooling trend that caused the world to dry out over the past 55 million years, also drove the spread of grasslands as well as ungulate herbivores grazing them. It was this global process that provided most of the crops we domesticated for agriculture.

ABOVE: Chogo Lungma Glacier in the Karakorum mountains in Pakistan

particular trigger such ice ages. This most recent ice age was in fact only one of a series of 40 or 50 ice ages over the past 2.6 million years. This in itself is something of a curiosity. Ice ages are actually pretty rare in Earth's history – in fact, for around 80 per cent of our planet's past there haven't even been ice sheets covering the north and south poles. We are in an unusually cool planetary period – for the past 55 million years the Earth has been getting slowly chillier, with great ice sheets first appearing on Antarctica, and then Greenland, and finally, around 2.6 million years ago, the open ocean around the North Pole began to freeze over.

One major contributor to this long-term global cooling was the crumpling up of the Himalayas as plate tectonics drove India crashing into Eurasia. As this towering mountain range has been eroded, gradually disassembled grain by grain, it has effectively absorbed carbon dioxide out of the atmosphere and reduced

AFTER CROSSING THE LAND BRIDGE, HUMANITY WALKED WHERE NO HOMININ HAD EVER TRODDEN BEFORE

ABOVE: Hominins migrated across the Bering land bridge

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this greenhouse gas. The freezing over of the North Pole marked the beginning of the most recent geological period – the Quaternary – and an exceptionally unstable time for the planet's climate, as it regularly see-saws between ice ages and warmer interglacial intervals. The most recent ice age began about 117,000 years ago.

As our ancestors migrated out of warmer Africa, the glaciation may have presented challenging conditions for those migrating north, but this most recent ice age also presented humanity with a crucial opportunity.

LAND BRIDGES

The expansive ice sheets and glaciers locked up huge amounts of water, and the sea levels around the world dropped by up to 120 metres. This exposed large areas of the continental shelves around the margins of the great land masses, and our ancestors were able to simply walk across dry ground through the East Indies and from New Guinea into Australia. But most crucially for the human story, the low sea levels of the ice age exposed the Bering land bridge linking Siberia and Alaska.

While earlier hominin species had migrated through Eurasia – some reaching as far as China – our ancestors became the first to make it into the Americas, sometime after 20,000 years ago. As our ancestors spread through Europe and Asia they mated with our cousin species the Neanderthals and Denisovans. But in America they encountered no previous peoples. After they crossed the Bering land bridge into the new world, humanity was walking where no hominin species had ever trodden before. When the ice age began to thaw again and sea levels rose, the peoples of the eastern and western hemispheres were once again separated from each other.

So, it was the combination of active plate tectonics in East Africa and cosmically-driven climate fluctuations that crafted us as a uniquely intelligent species, and the particular conditions of the most recent ice age that allowed us to simply walk around the globe to populate the entire planet.

The current interglacial period began around 11,500 years ago – the first that our ancestors had ever experienced out of Africa – and within just a few thousand years peoples all around the world began domesticating wild animal and plant species to provide the livestock and crops of agriculture. We settled down in ever more populous towns and cities as the social organisation and centralised coordination of civilisation emerged. And the rest, as they say, is literally history. SF

BBC FOUR

Watch clips from The Incredible Human Journey
bbc.in/2Ds1OIg

by **PROF LEWIS DARTNELL**
(@lewis_dartnell) Lewis is the author of Origins: How the Earth Made Us (geni.us/origins).

THE SECRETS OF HUMAN EVOLUTION

Scientists have been piecing together clues about the different species on the hominin family tree…

WORDS: **ISABELLE DE GROOTE**

Before the first fossils of our ancestors were unearthed, anatomists studied the differences between humans and our closest living relatives, the great apes, for clues as to our origins. Since then, the study of ancient human remains has given us a wealth of information about how humans evolved.

Until the 1930s, scientists believed that our bigger brain was the key characteristic that drove human evolution over our ape relatives. But over the last few decades, it's become clear that this early theory is wrong. Fossils of hominins (the evolutionary branch that includes humans and our extinct ancestors) are revealing more about the major steps that led to modern humans. The earliest hominin fossils – dating back six million years – show, for instance, that our ancestors walked on two legs long before their brains became bigger.

Certain physical features have made *Homo sapiens* the masters of the planet, enabling us to develop language, use tools and create art. And by examining every aspect of the body, from arms and ankles to feet and teeth, palaeoanthropologists are uncovering the anatomical innovations that have ultimately made us who we are. Over the page, we examine the skeletal remains of some species which mark key areas of human evolution.

ILLUSTRATION: MAGIC TORCH

AUSTRALOPITHECUS AFARENSIS

NICKNAME LUCY'S SPECIES
EXISTED 3.9 TO 2.9 MILLION YEARS AGO
HEIGHT 1.5M (MALES), 1M (FEMALES)
WEIGHT 40KG MALES, 30KG FEMALES

SKULL

The volume of the brain was around 450cm³ – similar to that of apes today. Although a larger brain size was initially thought to have developed first during human evolution, we now know that bipedal walking originated before, and that brains didn't become bigger until our ancestors started eating meat.

ARMS

Australopithecus afarensis had long arms relative to its legs. This feature is more like the body proportions of apes – with their long forearms and short legs – rather than humans, with their short arms and long legs.

HANDS

Curved, elongated fingers indicate *Australopithecus afarensis* had a very strong grip that was probably still grasping branches on trees to feed, build nests and avoid predators. A greater length of the thumb relative to the other fingers is the main similarity with humans.

FEET

Footprints fossilised in volcanic ash dating back 3.6 million years clearly show humans walking on two legs. In contrast, the foot bones of *Australopithecus afarensis* still show a mixture of human and ape characteristics: the big toe is almost in line with the rest of the toes and there's an indication of an arch as in humans. Still, the toes are long and curved for grasping, as in apes.

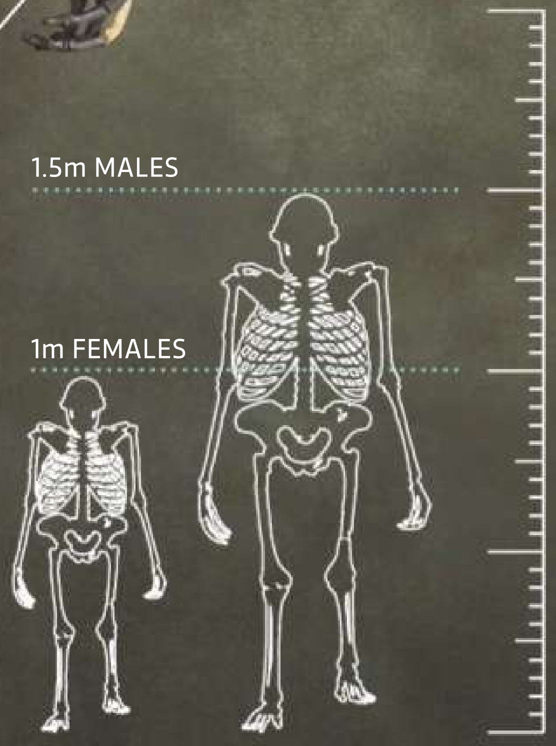
HIPS

The short and wide, bowl-like shape of the hip bone is typical of a bipedal walker, and it's very different from the high, narrow and forward-facing hip of apes. Its shape helps to support the upper body and reflects the large gluteus maximus buttock muscles. The hip of *Australopithecus afarensis* was even wider than that of humans, which may have affected its balance.

KNEES

The first piece of Lucy that was found was part of her knee joint and it clearly showed that, as in humans, the tops of the legs were far apart due to wide hips, but her knees were together. This keeps the centre of gravity in the middle while walking. When walking on two legs, apes stand and walk with their knees apart and will swing from side to side, which uses much more energy.

HEIGHT



Over 400 fossils of *Australopithecus afarensis* have been found across East Africa. One partial skeleton is especially well known though. When this female specimen was discovered at Hadar in Ethiopia by Donald Johanson in 1974, he and his team celebrated by repeatedly playing the Beatles song *Lucy In The Sky With Diamonds*. And so, the fossil was named Lucy.

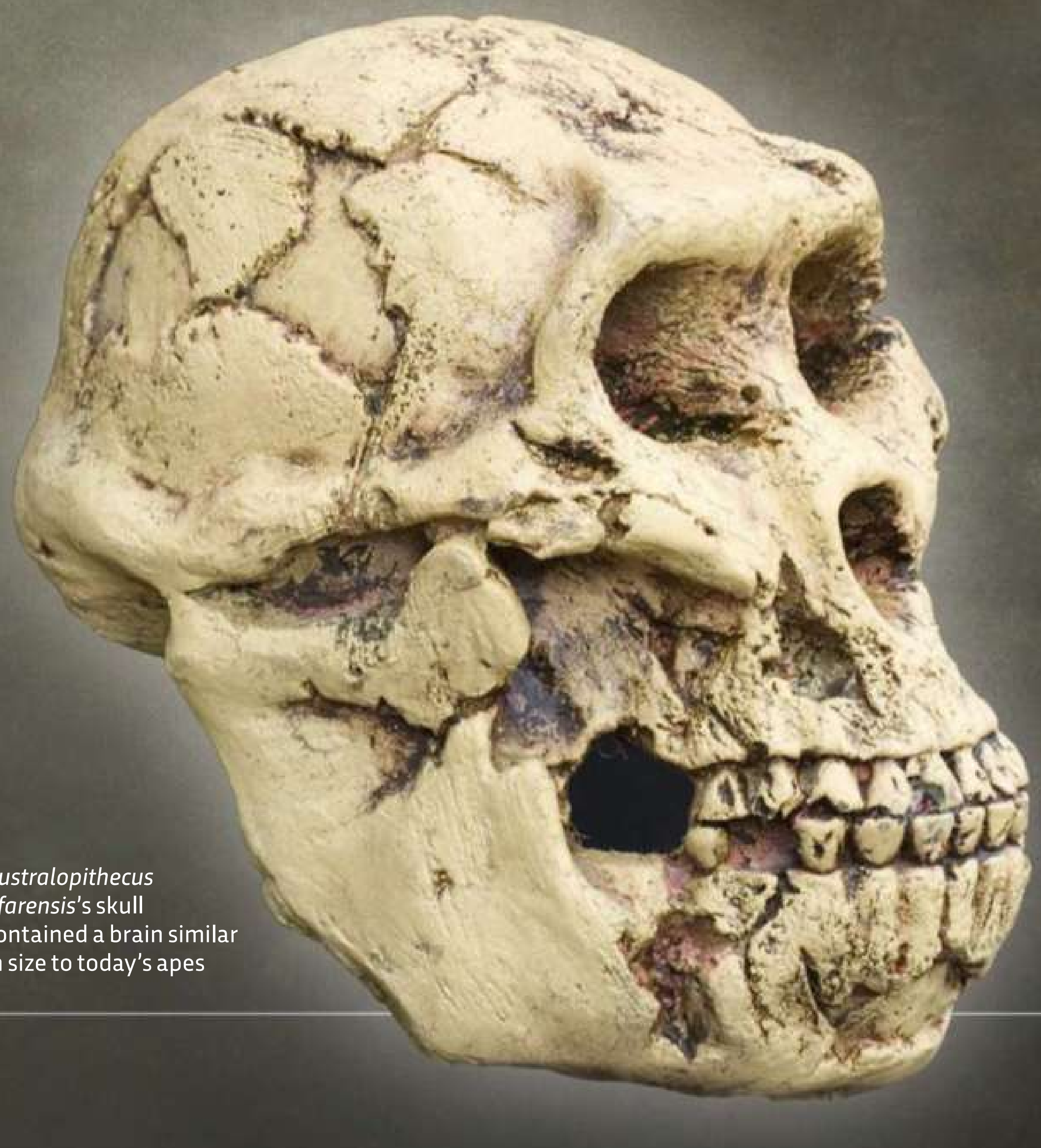
Australopithecus afarensis lived from 3.9 to 2.9 million years ago and shared much in common with modern apes. Curved fingers and toes, more mobile shoulders and relatively longer arms indicate that they would have relied on trees to build nests, escape from predators and collect fruit and nuts for food. Their brains were only a third the size of our own and wouldn't have taken as much time to grow. Babies developed as fast as apes do, which would have meant less learning before they reached adulthood, compared to modern humans. The males were also much larger than females and they probably lived in small family groups.

Despite having ape-like characteristics, *Australopithecus afarensis* is considered an early hominin. This is based on some distinctly human-like evolutionary changes, including smaller canine teeth and a hole in the skull where the spinal cord passes through to the body underneath, which shows that the head was carried above the body and not in front, as in apes.

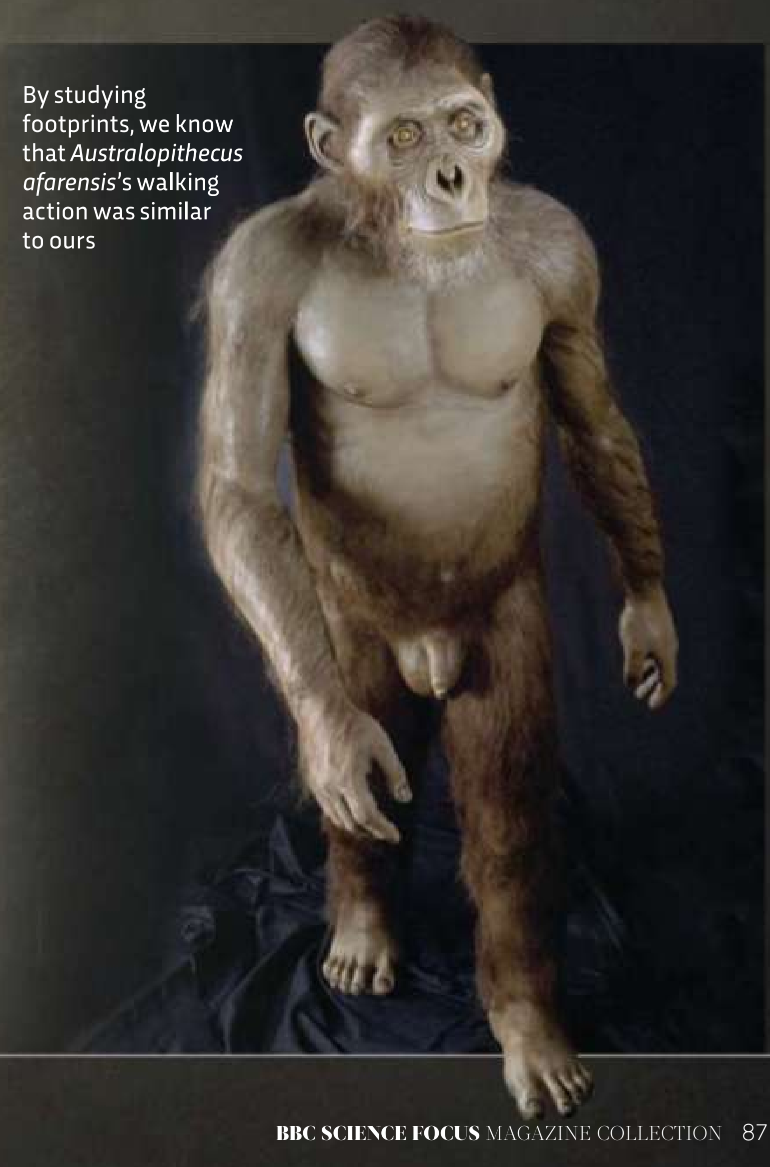
Most notably, there are several changes to the skeleton for walking on two legs: the hips are wide, short and bowl-shaped to carry the weight of the body, as in humans, while the legs angle inwards to bring the knees and feet together. These adaptations for bipedal walking enabled these early hominins to cover larger distances between food sources, with a range covering East Africa, and allowed our ancestors to survive the changing environment with which they were faced, from rainforests to woodlands.

PROF ALICE ROBERTS SAYS...

Our closest living relatives – chimps – stand on two legs. If that is the locomotion of choice to get from A to B then that causes changes in anatomy. Lucy's skeleton had these changes, and they were very similar to our skeletons. Another piece of evidence came from the 'Laetoli footprints' from Tanzania. Prof Robin Crompton from the University of Liverpool has studied Lucy's gait, primarily by analysing the Laetoli footprints and how they represent stepping onto the ground – compared with humans and chimpanzees. The way we form footprints reflects the pressures applied at different points, because the whole of your foot doesn't hit the floor at the same time: pressure comes through the heel, then down onto the ball and onto the toes. And when Robin looked at Lucy's footprint, it appeared to be quite similar to the way we walk."



Australopithecus afarensis's skull contained a brain similar in size to today's apes



By studying footprints, we know that *Australopithecus afarensis*'s walking action was similar to ours

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HOMO ERECTUS

NICKNAME UPRIGHT MAN
EXISTED 1.9 MILLION TO 200,000 YEARS AGO
HEIGHT 1.45M TO 1.85M
WEIGHT 40KG TO 68KG

SKULL

The brain was around $850cm^3$ in size – between that of humans and apes. It remained this size until *Homo erectus* started hunting animals and eating meat, a food source that yielded enough energy to allow larger brains to evolve.

HANDS

Although there are very few hand fossils for *Homo erectus*, it's believed their hands would have been much like ours. They made stone tools, including the typical tear-shaped hand axes. They would have used these and other tools for hunting and scavenging meat, and to process plants.

LEGS

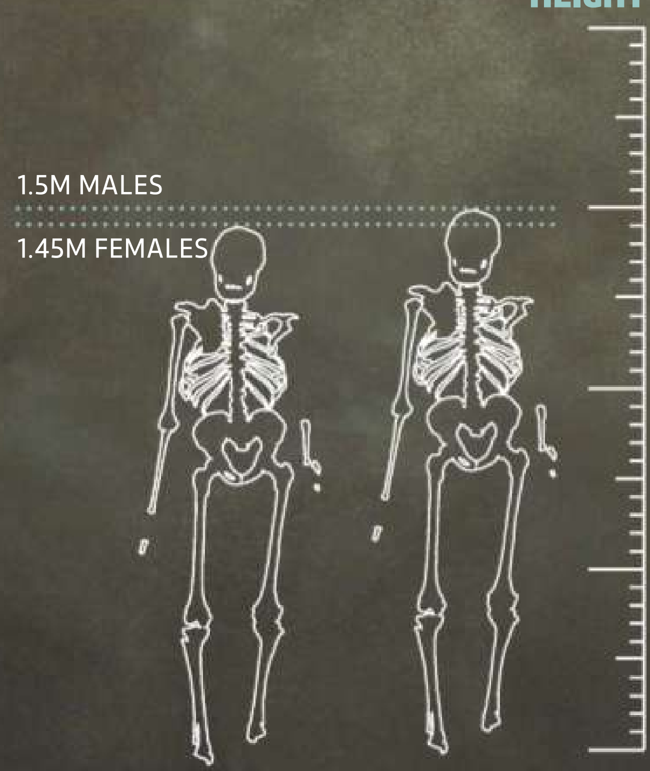
Homo erectus was the first species with long legs like ours. These would have made bipedal walking much more energy efficient than in early hominins, because longer legs allow a greater distance to be covered with fewer strides.

TEETH

Like counting growth rings in a tree trunk, scientists can calculate a person's age by looking at their perikymata – microscopic growth lines on the surface of tooth enamel. Counting perikymata on the teeth of Turkana Boy, the most complete *Homo erectus* specimen, show he was only nine years old when he died. His body was almost fully grown, however,

ARMS

Turkana Boy's skeleton demonstrates that, by 1.5 million years ago, our ancestors had human-like body proportions with long legs and short arms. This indicates that *Homo erectus* no longer relied on the trees, but lived permanently on the ground.



During human evolution, various hominin species arose but soon went extinct. *Homo erectus* was one of the exceptions: a long-lived and very successful species that walked the Earth 1.9 million to 200,000 years ago.

The most famous specimen is known as 'Turkana Boy', which was discovered in 1984 in Kenya. This almost complete skeleton provided the first definitive proof that the post-cranial skeleton (everything below the skull) was essentially human over a million years before the brain reached human size. Unlike apes, they stood up straight, hence their nickname: 'upright man'.

Their anatomy, along with tools found with fossils, show that *Homo erectus* was the first true hunter-gatherer. The body is adapted to long-distance walking and running. Biologist Dennis Bramble and anthropologist Dan Lieberman suggest these adaptations enabled them to hunt large mammals.

Without projectile weapons such as bows and arrows, *Homo erectus* may have been a persistence hunter that chased and tracked large animals to exhaustion, then killed them with fairly simple tools. Hunting would have provided meat, a high-energy food necessary to fuel bigger brains.

Although *Homo erectus* still grew up faster than humans today and therefore learned less before they reached maturity, they became a very successful species because they lived in family groups, co-operated, and may even have had a rudimentary form of language, allowing them to communicate. There's also fossil evidence that they cared for the old and weak.

All their abilities – being able to hunt, gather and use tools and fire – made it possible to survive in a range of environments. This enabled *Homo erectus* to not only spread across the whole of Africa, but to become the first human ancestor known to leave the continent.

PROF ALICE ROBERTS SAYS...

"There was a drying-out on the east side of Africa throughout the Pleistocene, so by 1.5 million years ago there was a significant expansion of grasslands. *Homo erectus* seems to have exploited this new environment. One suggestion is that when they walked out onto the savannah, they would've needed to lose heat. We're relatively hairless compared with chimpanzees, and sweating is an effective way of cooling down because there's no hair to trap the sweat and stop it from evaporating. It's impossible to say precisely when we lost our fur, but this might have been the point in time. One experiment I carried out with colleagues was to heat someone who was half-naked and someone wearing fur, then measured their temperatures to see how well they coped with heat loss. It revealed what would've been useful to our ancestors."

This *Homo erectus* skull was found at Sangiran on Java, Indonesia, showing how this species spread across the globe

Homo erectus was able to run, enabling it to hunt large mammals

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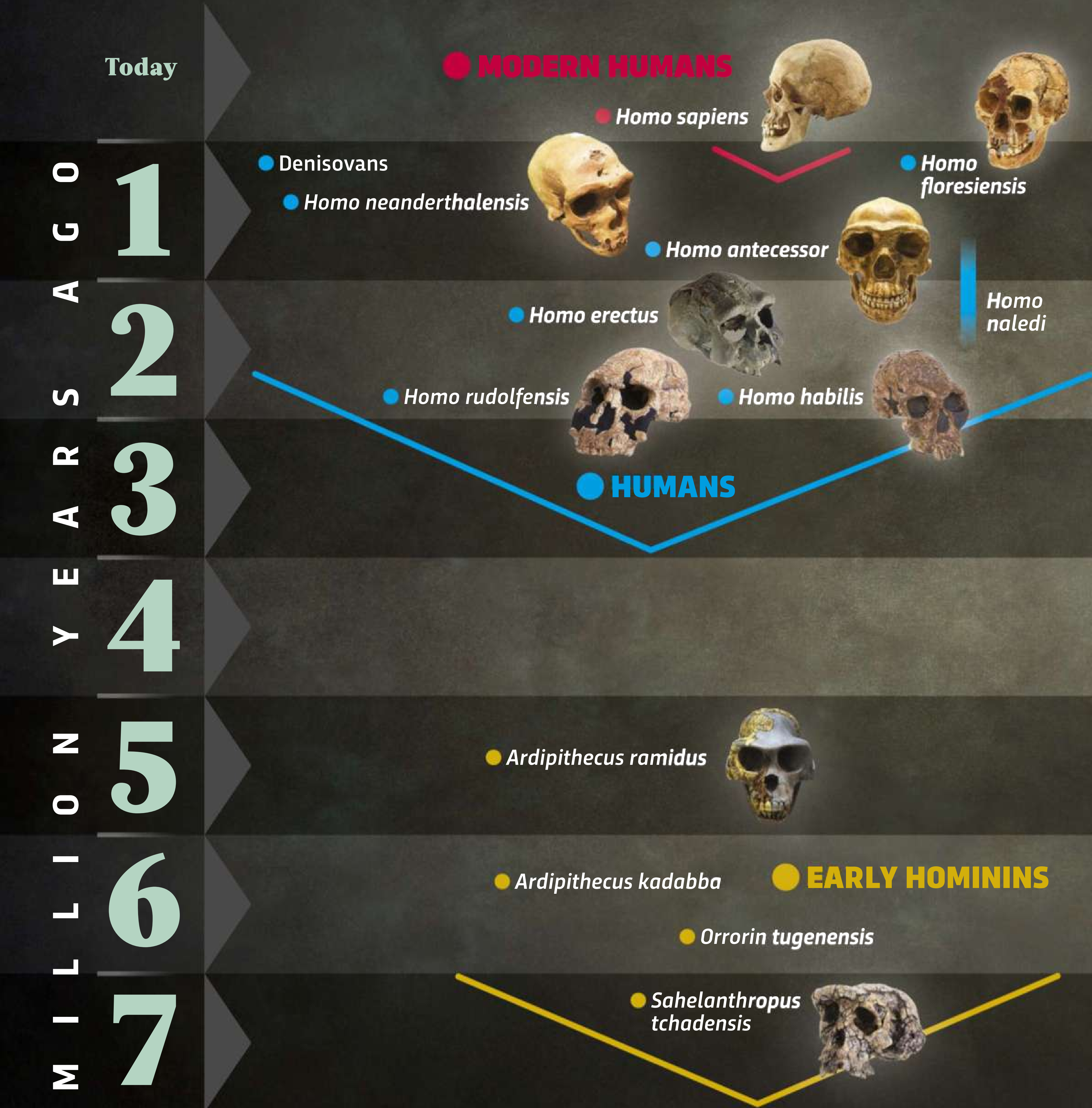
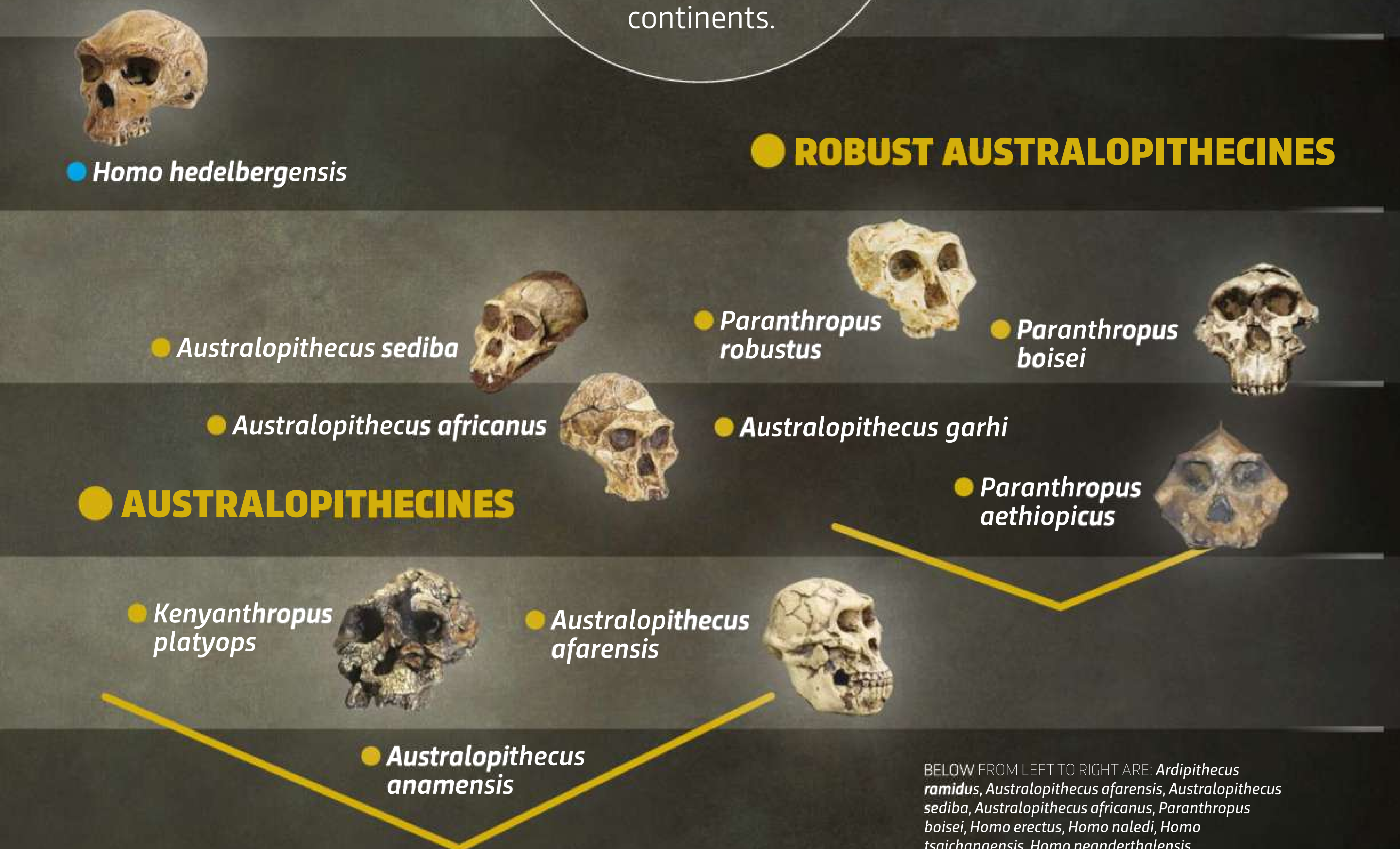
HOMININ FAMILY

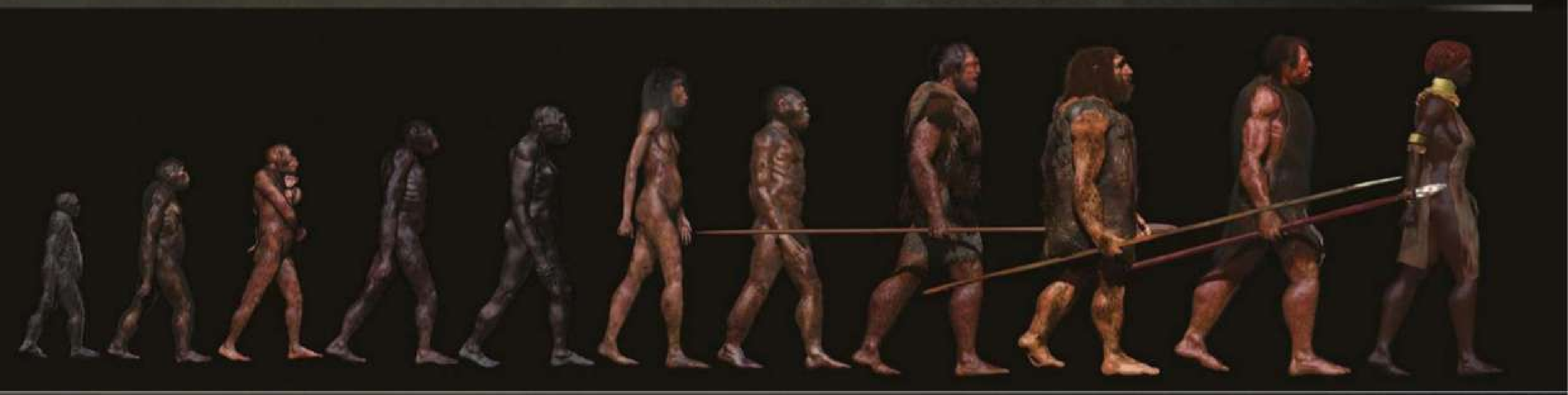


ALAMY X12, GETTY IMAGES X2, AKG X2, SCIENCE PHOTO LIBRARY, RAMA/WIKIPEDIA COMMONS

TREE

Human evolution didn't happen along one simple line of a family tree, but instead was a complex set of branches stretching out over many millennia and different continents.





BELOW FROM LEFT TO RIGHT ARE: *Ardipithecus ramidus, Australopithecus afarensis, Australopithecus sediba, Australopithecus africanus, Paranthropus boisei, Homo erectus, Homo naledi, Homo tsaichangensis, Homo neanderthalensis, Denisova hominin, Homo sapiens.*

HOMO ANTECESSOR

EXISTED AROUND 800,000 YEARS AGO
HEIGHT 1.6 TO 1.8M
BRAIN SIZE AROUND 1,000CC

WHAT DID THEY LOOK LIKE?

This species is so far only known from fossils found in a former cave site in Spain dated to about 800,000 years ago. They had unique features that distinguish them from other Homo fossils. Their bodies were similar in size to those of modern humans, with males being between 1.6m and 1.8m tall and females somewhat shorter. Their bodies were a little more robust than ours and their brain size was around 1,000cc, which is around 350cc smaller than the average modern human. Their faces had a modern-looking mid-face with a canine fossa (hollowed cheek), but also heavy brow ridges and a backward-sloping forehead.

HOW DID THEY LIVE?

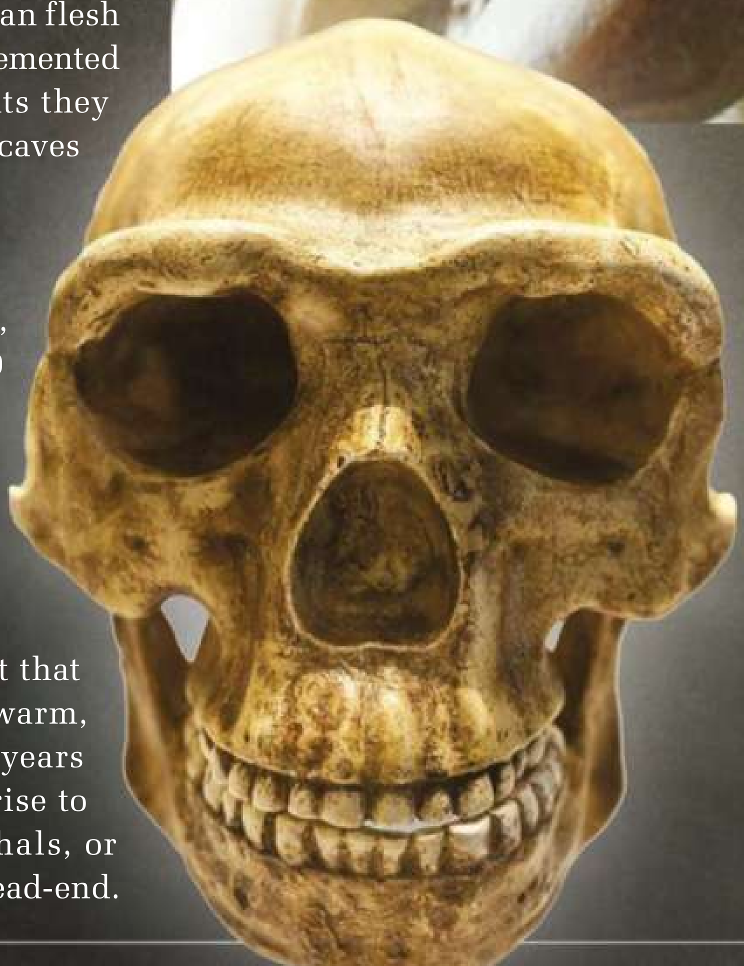
Homo antecessor lived as hunter-gatherers. Their diet may have contained large amounts of meat, acquired either through hunting or scavenging. They produced fairly simple 'Oldowan' stone tools from local raw materials and used them for processing and eating meat and marrow. Cut marks on some human bones suggest they may have consumed human flesh from time to time. They probably supplemented their meaty diet with plants and fruits they collected. They were nomadic, using caves as temporary shelter while hunting.

WHERE DID THEY LIVE IN BRITAIN?

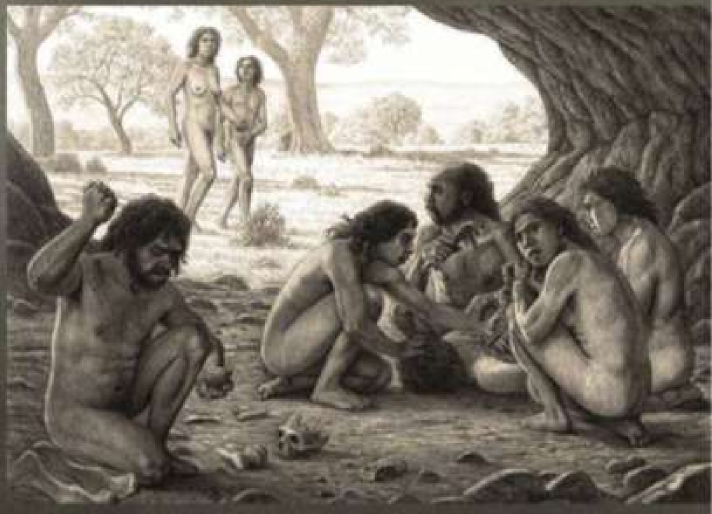
Footprints found in Happisburgh, Norfolk, dating back to between 850,000 and 950,000 years ago, may have been made by *Homo antecessor*. They may have been the first hominin to reach Britain.

WHAT HAPPENED TO THEM?

Animal remains at fossil sites suggest that in *Homo antecessor*'s heyday it was warm, but this changed about 700-650,000 years ago. It is unclear whether they gave rise to *Homo heidelbergensis*, to Neanderthals, or whether they were an evolutionary dead-end.



Homo antecessor may have dined on each other. The image below shows a scene from the Sierra de Atapuerca in Spain, where cave excavations found evidence of cannibalism – cut and scrape marks on human and animal bones, suggesting tendons and flesh were removed from the bones with stone tools



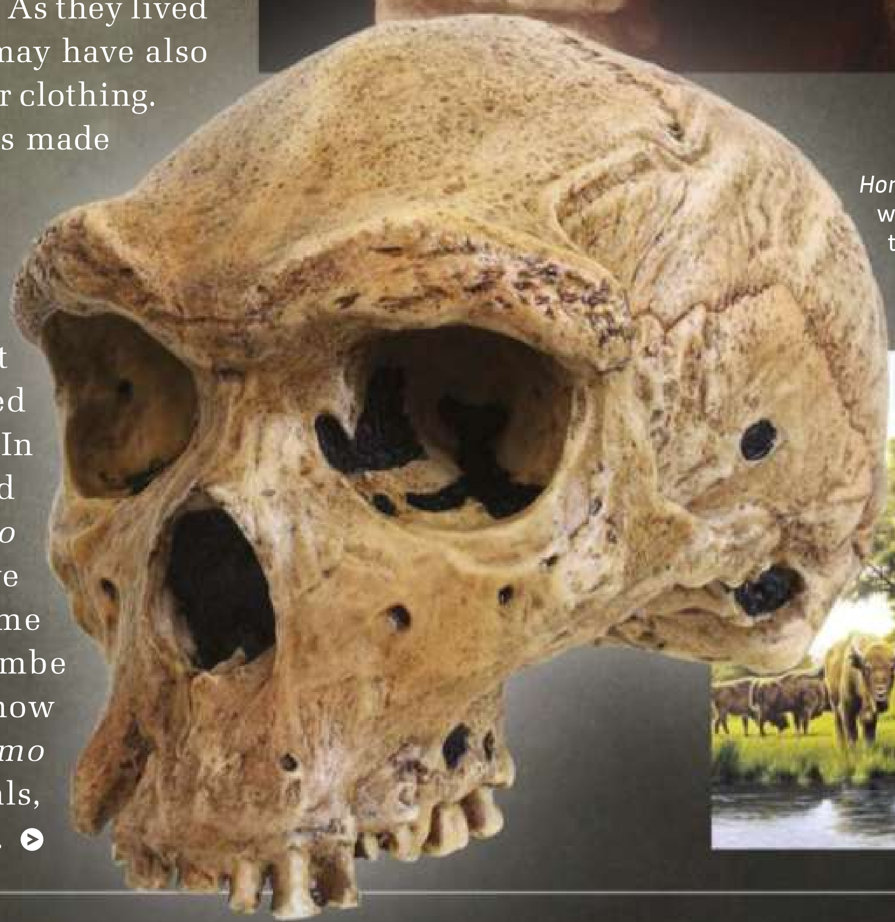
HOMO HEIDELBERGENSIS

EXISTED AROUND 600,000 YEARS AGO
HEIGHT 1.55M TO 1.75M
BRAIN SIZE AROUND 1,250CC

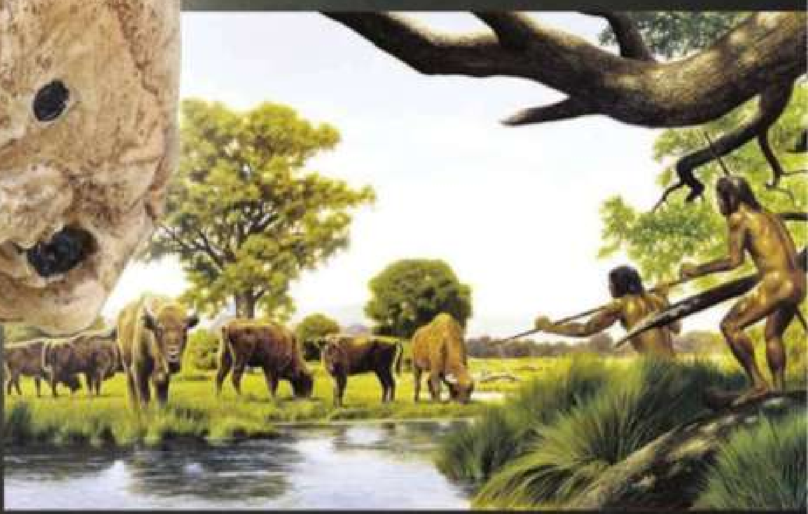
WHAT DID THEY LOOK LIKE?
Believed to be ancestors of both modern humans and Neanderthals, *Homo heidelbergensis* evolved at least 600,000 years ago, and by 500,000 years ago had probably spread across Africa, southern Asia and Europe. They were tall and strong. Like *Homo antecessor*, their faces were still dominated by strong brow ridges and sloping foreheads, but their brains were on average 1,250cc and show increased brain complexity. *Homo heidelbergensis* is the earliest human species for which we have fossil evidence in Britain. From tibia fossils found at Boxgrove, it has been shown that it was taller than the later, cold-adapted Neanderthals.

HOW DID THEY LIVE?
Large stone tools used by *Homo heidelbergensis* have been found at a number of sites in Britain: High Lodge, Brandon Fields and Waverly Wood to name a few. These tools were more varied than those of *Homo antecessor*, and included bifacial handaxes, cleavers and scrapers. *Homo heidelbergensis* were probably skilled hunters of large animals, such as hippopotamus, rhinoceros, bear, horse and deer. As they lived in colder areas, these animals may have also been important for hides used for clothing. There is some evidence for tools made from antler, bone and wood.

WHAT HAPPENED TO THEM?
Homo heidelbergensis began to adapt to the local environment in which they lived and started to develop regional differences. In Africa, they eventually evolved into our own species, *Homo sapiens*, and in Europe they gave rise to the Neanderthals. Some fossils, such as the Swanscombe cranium, have features that show the transition between *Homo heidelbergensis* and Neanderthals, so classification is controversial.



Homo heidelbergensis were skilled toolmakers. The scene below shows them hunting bison in what is now the Atapuerca Mountains in Spain. They hunted in groups, allowing them to kill large prey



HOMO NEANDERTHALENSIS

NICKNAME NEANDERTHALS
EXISTED 200,000 TO 30,000 YEARS AGO
HEIGHT 1.55M TO 1.7M
WEIGHT 40KG TO 90KG

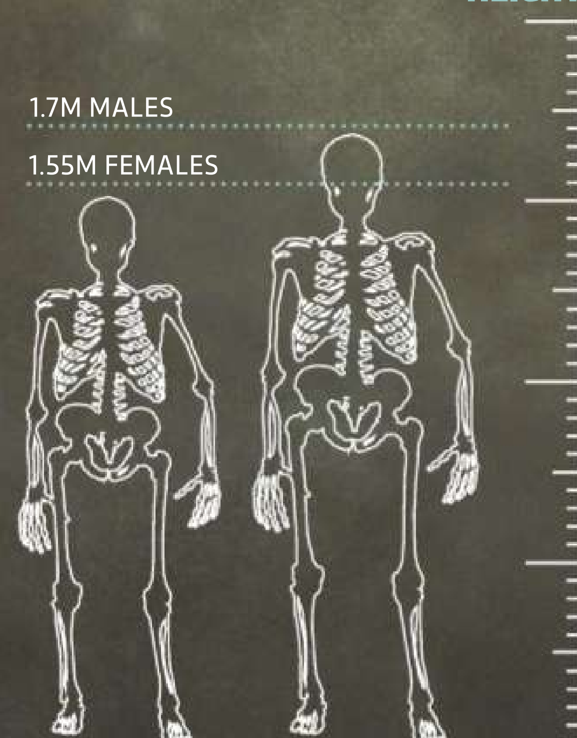
SKULL
Neanderthal brains were as large as – and sometimes larger – than that of modern humans. Their skulls still looked primitive, with heavy brow ridges and no chins. They had large noses to heat up the cool, dry air of Ice Age Europe.

ARMS
Neanderthal arms and hands were very strong. The shoulder and arms were adapted to spear thrusting. There's clear evidence that Neanderthals hunted big game, and that they frequently suffered hunting accidents too.

CHEST
The chest of the Neanderthal was wider and more funnel-shaped than that of modern humans. Their bodies were shorter and stockier than ours. Today, humans living in cold climates have a similarly stocky build to preserve heat, but in Neanderthals this adaptation was even more pronounced because the ice ages were so cold – and they didn't have tailored clothing.

LEGS
The lower parts of Neanderthal legs were shorter than that of humans, with large knees and curved thighbones reflecting their active hunter-gatherer lifestyle. They would often have carried heavy objects over long distances.

HEIGHT



ANKLES
Features in the ankles of Neanderthals show that they couldn't run as well as modern humans over long distances. Instead, their feet may have been better adapted to hunt with ambush strategies and sprinting, so they therefore didn't require a long-distance running ability.

Although fossils of *Homo neanderthalensis* were first discovered in Belgium in 1829, they weren't recognised as an early human ancestor until a partial skeleton was found in Neanderthal, Germany, in 1856. Hundreds of fossils have since been found, making them our best understood relatives.

Neanderthals lived in the cold climate of Europe and Asia around 200,000 to 30,000 years ago, and they were well adapted to life in their harsh environment: short, stocky bodies and short limbs helped to retain heat in the core while also reducing surface area where heat could be lost. Their noses were huge and probably served to heat and humidify the cold, dry air before it passed down to the lungs.

It's possible Neanderthals were as intelligent as early *Homo sapiens* because their brains were as large, and sometimes larger, than ours. But their skulls still had a primitive large brow ridge and were elongated and flattened in shape.

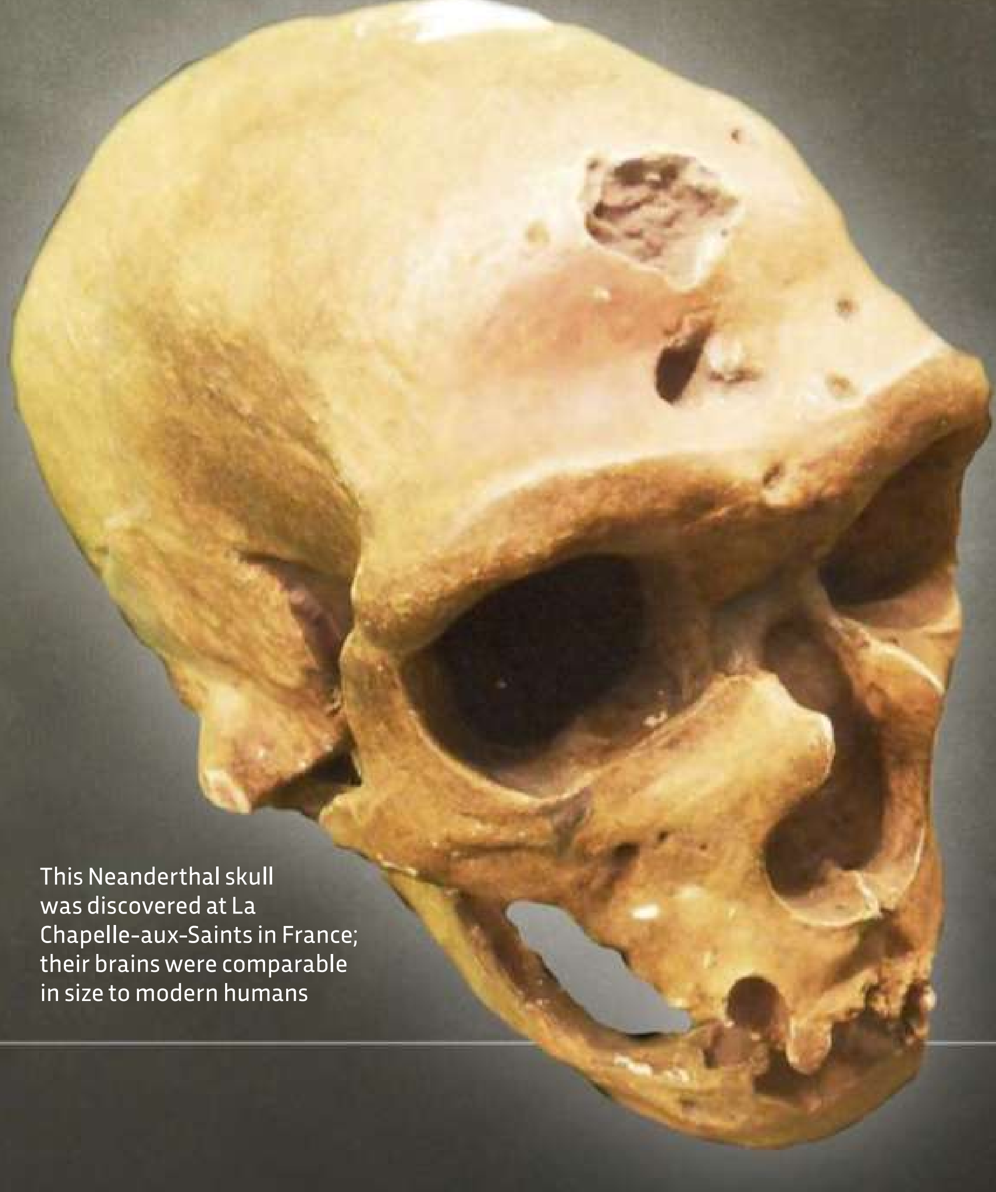
The way of life for Neanderthals was very similar to that of early modern humans – living in caves and probably wearing clothing. They were also skilled at making tools to hunt large animals like mammoths, and they gathered fruit, legumes and nuts. In terms of culture, they almost certainly used language and even buried their dead – a sophisticated behaviour not seen in other extinct hominins.

Comparing Neanderthal DNA to that from modern humans has provided fascinating insights. For example, it's clear that when humans left Africa and reached Western Asia, they interbred with Neanderthals – people of non-African heritage carry up to three per cent Neanderthal DNA.

Although Neanderthals thrived in Ice Age Europe, they were likely out-competed by the newly-arriving modern humans, and went extinct within about 10,000 years of humans arriving in Europe.

PROF ALICE ROBERTS SAYS...

"Could Neanderthals throw? There are clues in their anatomy. Archaeologist Dr Colin Shaw has looked at modern humans who regularly throw things and compared the shape of their bones to Neanderthal bones. Shaw reconstructed the cross-sectional shape of the Neanderthal humerus (the upper arm bone) and what that meant in terms of whether they could throw. We tend to think of our bones as being almost dead because we see skeletons preserved in the ground, but it's a living tissue. If you break a bone, it will repair itself. It's an amazing tissue. Bones are plastic – they respond to their mechanical environment – so the shape tells you something about how a person used their arms during life. If you looked at the tennis player Andy Murray's arms, his humerus would probably be larger on the racket-playing side."



This Neanderthal skull was discovered at La Chapelle-aux-Saints in France; their brains were comparable in size to modern humans

Neanderthals were adapted to survive the extreme cold of the Ice Age

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WHERE THEY LIVED

Hominin species have made many forays into Britain over the millennia, with sites found all over England and Wales

LINKS WITH EUROPE

Changing sea levels and encroaching ice sheets made the land bridge come and go

1,000,000 YEARS AGO

With a warm climate, *Homo antecessor* was able to occupy northern Europe

450,000 YEARS AGO

The most severe cold period saw ice sheets cover much of Britain

400,000 YEARS AGO

A warming climate enabled early Neanderthals to colonise Britain

60,000 YEARS AGO

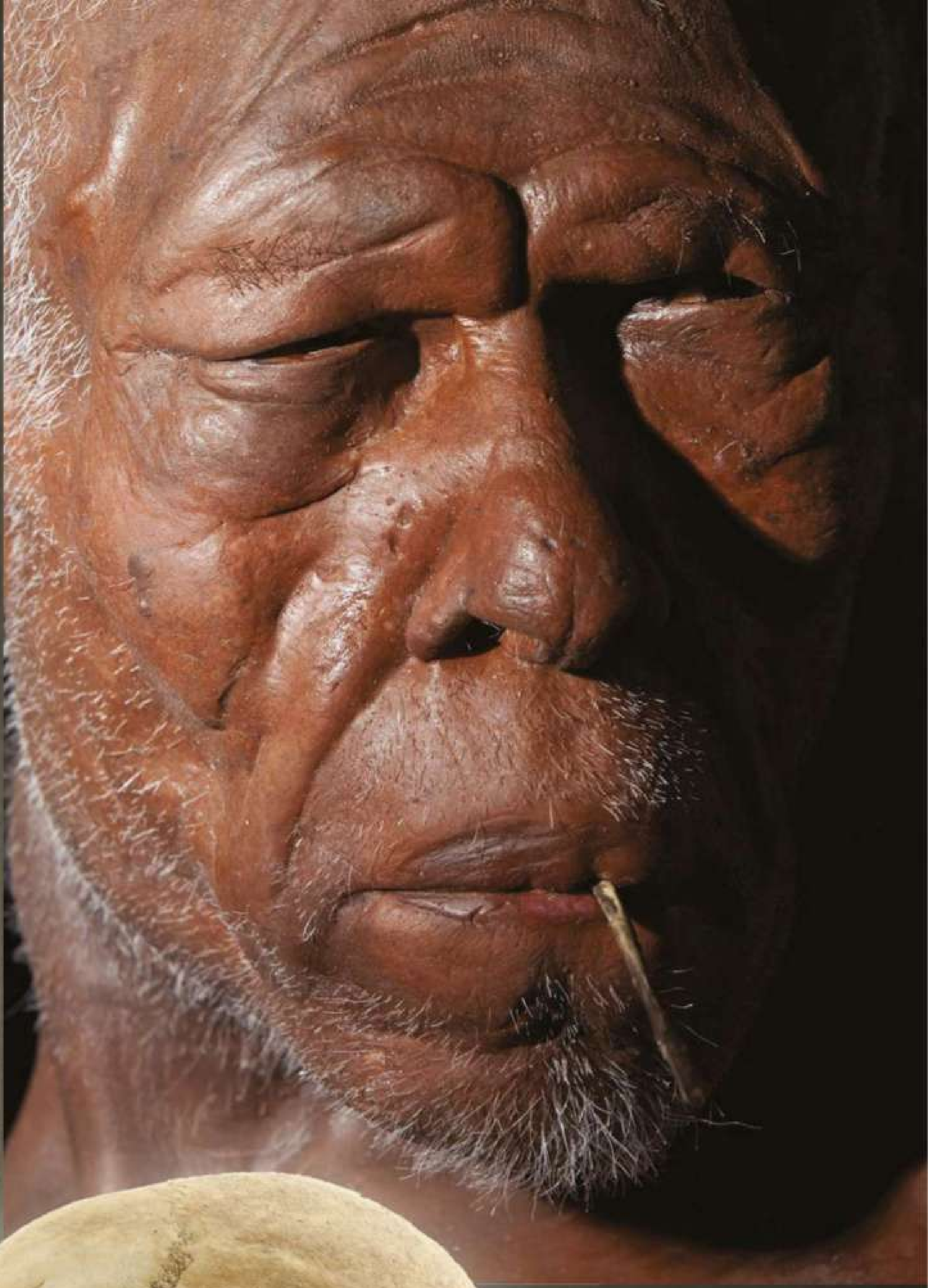
Neanderthals thrived and were widespread across Britain

15,000 YEARS AGO

Sea levels were still low and humans returned over the final land bridge

HOMO SAPIENS

EVOLVED AROUND 200,000 YEARS AGO
BRAIN SIZE AROUND 1,300CC



WHO DID THEY EVOLVE FROM?

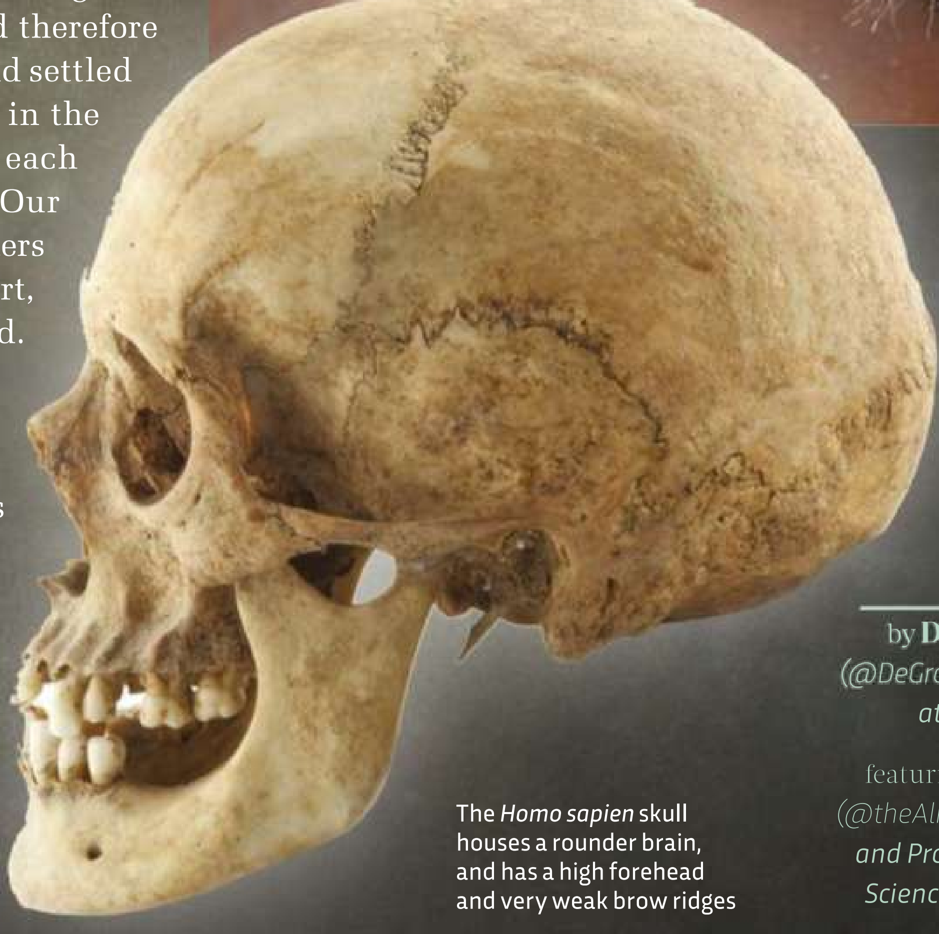
Homo sapiens is the species to which all humans now living on the planet belong. Modern humans evolved in Africa, probably from *Homo heidelbergensis*, and are characterised by a more lightly built skeleton. We have large brains with an average size of 1,300cc. The part of our skull that houses the brain is rounder, with a high forehead and very weak brow ridges.

HOW DID THEY LIVE?

The first modern humans were still hunter-gatherers. The most important difference between modern humans and previous human species is our ability to innovate at a rapid pace. Tools became more complex, refined and specialised for different tasks such as hunting, fishing, sewing and storing. As modern humans became more skilled and therefore able to adapt to living in different environments, they rapidly spread across the world. Within the past 12,000 years, some humans figured out that they could control the breeding and growing of animals and plants, and therefore invested time in food production and settled down. Modern humans are unique in the ways in which they interact with each other and with their environment. Our bigger brains enable us to build shelters and social networks. We also create art, music, rituals and a symbolic world.

WHEN DID THEY FIRST LIVE IN BRITAIN?

Britain has been connected to the European mainland for most of its history, so it's no surprise that ancient humans eventually found their way here. Since then, different human species have made many forays into Britain over the millennia, with sites found all over England and Wales. *Homo sapiens* first immigrated here around 42,000 years ago. SF



The *Homo sapien* skull houses a rounder brain, and has a high forehead and very weak brow ridges

GETTY IMAGES

BBC RADIO 4

Listen to an episode of The Infinite Monkey Cage *where Alice Roberts and Brian Cox talk about human and Neanderthal interbreeding*
bbc.in/2ShFqKO

by **DR ISABELLE DE GROOTE**
(@DeGrooteI) Isabelle is an anthropologist at Liverpool John Moores University.

featuring **PROF ALICE ROBERTS**
(@theAliceRoberts) Alice is a BBC presenter and Professor of Public Engagement with Science at the University of Birmingham.

The woolly mammoth

Fifty thousand years ago, Siberia looked very different from how it does today. Instead of forest and scraggy tundra, the region was blanketed in lush grasslands and fertile soils, and herds of woolly mammoths roamed the open plains. Then little by little, towards the end of the last Ice Age, their numbers started to diminish. No one really understands why. Some blame human hunting, some climate change, others a bit of both. What we do know is that they disappeared from Siberia 10,000 years ago, then from their final hiding place – a northerly island called Wrangel – just 3,700 years ago. Now Siberia is a massive mammoth graveyard, and it's estimated that the remains of hundreds of thousands of individual animals lie buried in the permafrost.

FACT FILE

LATIN NAME: *Mammuthus primigenius*

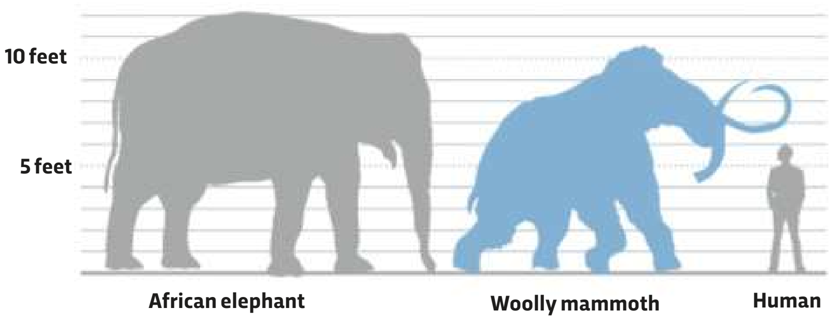
LIFESPAN: About 60 years

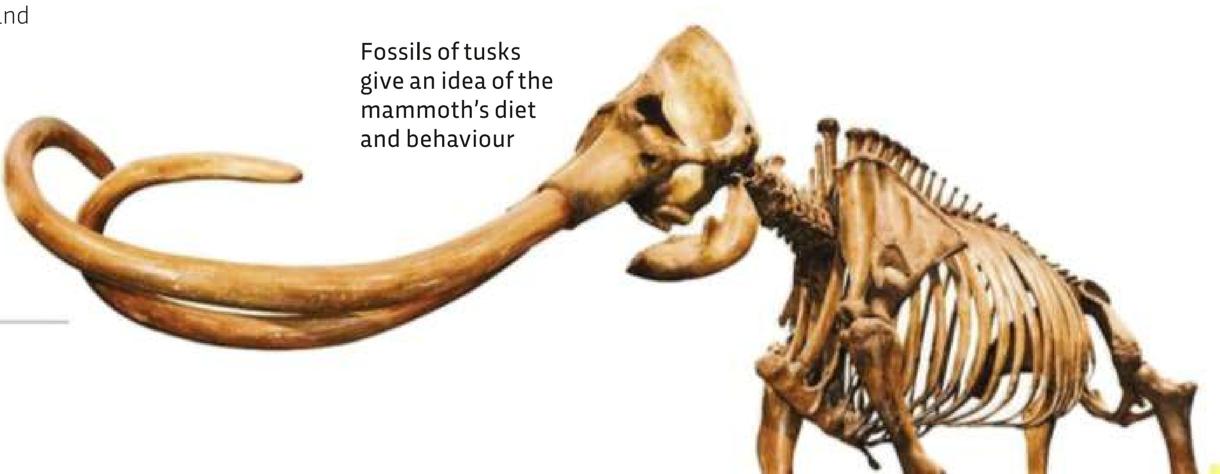
CLOSEST LIVING RELATIVE: African elephant (*Loxodonta africana*)

SIZE: Adult males stood up to 3.4m tall and weighed up to seven tonnes (that's about the same as three London black cabs)

RANGE: Africa, Europe, Asia and North America

LIVED: From the Pliocene epoch (5 million years ago) until the end of the Pleistocene (10,000 years ago). A tiny, isolated population survived on Wrangel Island in the Arctic Ocean until 1650 BC





Fossils of tusks give an idea of the mammoth's diet and behaviour

Discover the story of life on Earth: how it began, the earliest creatures, how dinosaurs conquered the world, what the first mammals looked like, and how humans spread across the planet.

FROM THE MAKERS OF ***BBC SCIENCE FOCUS*** MAGAZINE